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Enhancing Innovation Through Biologically Inspired Design[1]

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Abstract: Mixing upper level undergraduates majoring in engineering with those majoring in biology, we have devised a course on biologically-inspired design (BID) that provides practical training in methods and techniques that facilitate the identification and translation of biological principles into solutions for human challenges. The challenges of interdisciplinary courses generally, and the specific challenges of fostering exchange among biologists and engineers lead us to define these learning goals: (1) basic knowledge of successful examples of BID, (2) interdisciplinary communication skills, (3) knowledge about domains outside of their core training, (4) a uniquely interdisciplinary design process, and (5) how to apply existing technical knowledge to a new discipline**.** We developed the following course components to meet the key learning objectives: BID Lectures; Design Lectures; Found object exercises; Quantitative assessments; Analogy exercises; Research assignments; Interdisciplinary Collaboration, Mentorship; Idea Journals and Reflections. We will provide an extensive description of these elements, which we have chosen to incorporate based on our own experience with interdisciplinary communication, as well as findings from cognitive science regarding how students actually learn. This 15 week course is organized using assignments of increasing complexity that allow students to learn and apply essential skills of BID methodology and practice. Early exercises, which combine lectures, group discussions and individual assignments, have these objectives: 1) allow students to develop the necessary inter-disciplinary communication and research skills to facilitate their design project work; 2) expose students to ideation and design skills that will encourage them to work outside of their comfort zone; 3) practice the analogical reasoning skills that facilitate the successful search for and application of relevant

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biological concepts. This initial portion of the course stresses that BID occurs at the early phase of a design process and that identifying solutions from the biological domain requires that students have a sufficient breakdown of their problem combined with sufficient biological knowledge to suggest appropriate mappings between problem and solution. Two primary barriers are a lack of appreciation for how the evolutionary "design" process differs from human design, and the use of different terminology for describing similar processes in biology vs. engineering. We describe some teaching practices and activities that allow students to overcome these difficulties. The course culminates in a group project, which is a detailed conceptual design including a preliminary analysis of expected performance, value, and feasibility. A unique feature of the course is that it represents the efforts of not only biologists and engineers, but also contributions from cognitive scientists engaged in understanding human cognition and creativity. Our course strategy has been deeply influenced by findings in that field. We have studied the activity of classroom participants for the last three years, examining the processes they use, and intermediate and final design representations. Analysis of this has yielded a number of observations about the cognitive process of biologically inspired design that may provide insights regarding how to enhance BID education, as well as provide useful insight for professionals in the design field.

Key words: biologically-inspired design (BID); interdisciplinary communication

INTRODUCTION

Biologically inspired design (BID) represents a powerful and logical bridge to multidisciplinary education. Biologists and other scientists implicitly understand general principles relevant to function and design. Biologists and engineers each face the problem of identifying design criteria, yet each approaches the problem from a unique perspective. Mixing upper level undergraduates majoring in engineering with those majoring in biology, we have devised a BID class that provides both increased content knowledge in areas relevant to BID, as well as practical training in methods and techniques that facilitate the identification and translation of biological principles into solutions for human challenges. The output of the course is a conceptual design that incorporates biological principles into a device or process, as well as an account of how the problem was analyzed in order to facilitate the search for useful biological principles.

Our concerns in devising this course are related to both developing an approach that will facilitate BID, but also in addressing concerns about the novelty and utility of current practices in science, technology, engineering and math education. The logical connection between engineering and biology provided by BID as a problem solving activity provides an excellent atmosphere in which to encourage interdisciplinarity and develop sound pedagogical practices. To that end, we have incorporated elements from the field of cognitive science to understand potential pitfalls in our teaching approaches, evaluate the way students actually problem solve in our BID course, and evaluate the student designs. This has given us a unique and extremely valuable perspective on our pedagogical methods.

We focus this article on our five learning objectives to implement education innovation and using BID: (1) novel techniques for creative design, (2) interdisciplinary communication skills, (3) knowledge about domains outside of their core training, (4) a uniquely interdisciplinary design process, and (5) how to apply existing technical knowledge to a new discipline. We developed the following course components to meet the key learning objectives: BID Lectures; Design Lectures; Found object exercises; Quantitative assessments; Analogy exercises; Research assignments; Interdisciplinary Collaboration, Mentorship; Idea Journals and Reflections. Below, we describe our course components in overview and link them to specific learning objectives. We also provide some detailed descriptions of areas that we find either particularly troublesome or approaches that seem essential for success. Because the knowledge content of any particular course in BID is likely determined by the specific area (e.g. biologically-inspired robotics) or design challenge (e.g. energy efficient structures), our focus is more on the process level. That is, we believe it is more valuable to describe <u>how</u> we say things, and <u>why</u> we do so, rather than <u>what</u> we cover.

COURSE OVERVIEW

The class is an honors level undergraduate course, taught once a year and is available to all third, fourth and fifth year engineering, biology, and biomedical engineering majors. The 2009 class roster is typical of the course make-up, consisting of: 15 biology students, 11 mechanical engineering students, 2 biomedical engineering students, 2 chemical engineering students, 2 industrial engineering students, and 1 student each in material science; mathematics; aerospace engineering; nuclear engineering; environmental engineering; electrical engineering; polymer, textile, and fiber engineering; and earth and atmospheric science. **Table 1** shows how the class has changed over the past 5 offerings in terms of # students as well as lessons learned and modifications tested in next offering.

TABLE 1: Evolution of Undergraduate Biologically Inspired Design Course, 2005 – 2009

1.	**BID Class, Fall 2005**	**BID Class, Fall 2006**	**BID Class Fall 2007**	**BID Class Fall 2008**	**BID Class Fall 2009**
2. Students	12, 4 biologists	45, 10 biologists	45, 10 biologists	45, 20 biologists	40, 20 biologists
3. Studies	Classroom observations	In situ cognitive study	In class experiments, ME class experiments	Classroom observations	Analysis of final portfolios
4. Findings/ New approaches	Found objects, Idea Journals	Optimal duration of expert lectures, design fixation, solution/problem driven processes	Different representations among different groups, SBF, compound analogy, enhanced variation	Disbelief in real-world value of process, proof-of-concept experiment design requires new skills.	Greater satisfaction with final designs; repeated practice embeds BID process
5. Changes	Initial seminar (2 credit) class.	Expanded to full 3-credit course. Full interdisciplinary cross-listing.	Incorporated solution and problem driven design process, SBF lecture, functional decomposition	Increased emphasis on ideation, changes to SBF language, analogy emphasis, restructured design project	Three design iterations; structured feasibility analysis.

<u>NOTES:</u> At Georgia Tech, an upper level undergraduate class in biologically inspired design has now been offered 5 times (line 1). The ratio of biologists increased (see line 2: total # of students, # biologists). Findings (line 4) from various class studies (line 3) enabled us to modify the assignments (line 5), balance the class between lectures and design practice, improve cross disciplinary interactions, and evaluate the value of class-formulated bio-inspired designs. (Abbreviations: SBF = structure-behavior-function, ME = mechanical engineering, BID = biologically inspired design).

The ratio of biologists to engineers is now approximately 3:5. Initial classes were more heavily engineering oriented (with a 1:4 biologist to engineer ratio), but we found this didn’t work as well for at least three reasons. First, it placed too much workload demand on the single biologist on each five person project team. Second, when engineers were the overwhelming majority, the classroom environment was pragmatic, critical and generally quiet and restrained. Changing the class mix had an easily perceptible impact, increasing inter- and intra-team communication, in-class idea generation, and participation from non-engineering students. Finally, as a result of a local academic culture that places engineers “higher in the pecking order” than biologists and other disciplines, the additional number of biologists provides heightened emphasis on the biologists’ importance to the process and generated greater receptiveness to biological concepts.

COURSE COMPONENTS

Over the evolution of the BID, we developed the following course components to meet the learning development objectives:

Domain Content Lectures

We provided active practitioners of biologically inspired design with between 180-210 minutes of classroom (e.g. 6-8 lectures) time to (a) teach students the engineering principles of the biological organisms they studied, (b) demonstrate research principles for applying engineering techniques to understanding biological systems, and (c) illustrate the application of those principles to engineering design [French, 1994; Vogel, 1998]. These lectures contain deep biology and engineering content specific to particular organisms, enhancing student domain knowledge, and providing examples of interdisciplinary communication and knowledge application [Project Kaleidescope, 2004; Handelsman et al., 2004; DeHaan, 2005; Jacobsen and Wilensky, 2006].

Domain content lectures by local experts are universally appreciated by students, span a breadth of topics, and motivate the students by showing them real-world applications of the discipline. The primary function of these lectures is to provide students with the necessary knowledge outside of their core training, and give them exposure to creative designs involving BID. The necessity for understanding and discussing material outside their core expertise also gives them practice in interdisciplinary communication.

Design Lectures

Industrial design and design cognition experts teach the fundamental processes of biologically inspired design [detailed in Helms et al., 2008a; Pahl and Beitz, 1999; Ullman, 2003; Schild et al., 2004], brainstorming and ideation techniques [Dugosh et al., 2000], problem decomposition, and analogical reasoning. We believe this is an essential element because most undergraduate biology students have no design experience, and much of the engineer’s experience is in closed design problems. The open-ended nature of many BID projects requires a different approach, and so we devote 45-90 minutes of design lectures early in the course. This provides sufficient exposure so students are more comfortable with their design challenges, but this is clearly not an exhaustive exposure to design methodology.

Found object exercises

Most students have little knowledge of how biological processes perform particular functions, the range of different ways these functions are achieved, how the solution principles differ from human technology, or how to describe these systems in a way to encourage further study. To address these issues, students are asked to more closely investigate different aspects of locally available biological systems using a what-why-how-why framework [an analogue to the Structure-Behavior-Function framework: Goel, 1991a, 1991b; Goel et al., 2009]. Found object exercises provide students with a wide range of exposure to natural objects, as well as an appreciation for the sophistication of solutions developed by everyday natural objects [Vogel, 1998; Ball, 2001; Vincent, 2002]. Each exercise requires students to examine objects as representative of certain functions, thus for a given biological mechanism asking the questions “(structure) *what* are the relevant components of the system? (function) *why* does the system require the mechanism?”?

(behavior) *how* do the components interact to execute the mechanism?" *What-why-how* (WWH) analysis of the found object exercises are paired with expert lectures, such that students are asked to identify and analyze found objects that are related to upcoming expert lectures. The hands on interaction provides unique learning experiences (students often conduct impromptu experiments on their objects, such as putting a pinecone in a 400 degree oven to see how it reacts to intense heat), encourages interdisciplinary interaction using multi-modal representations [Chiu and Shu, 2007; Chiu and Shu, 2005; Vincent and Mann, 2002; Vincent, 2002], and increases student engagement. Many students are forced to rethink their prior conclusions about natural functions and capabilities as a result of this analysis.

Quantitative assessments

Engineers frequently use sophisticated quantitative analysis, which is unfamiliar to biologists. Such analysis often is presented by our guest lectures. We require students to use standard quantitative engineering techniques to evaluate biological systems such as spider silk and gecko adhesion [Arzt et al., 2003; Blackledge and Hayashi, 2006]. Engineering students gain new appreciation for the operation of biological systems whereas biologists learn techniques that may help them evaluate the performance of biological systems in their future work. Both engineers and biologists gain increased understanding of how to evaluate constraints in the system and the importance of those constraints in applying principles as solutions. This activity prepares students for the more extensive analysis such as material analysis, performance metrics and environmental impact assessments, required as part of their design project.

Analogy exercises

Students practice making cross domain analogies [Qian and Gero, 1996; Goel, 1997; Goel and Bhatta, 2004; Zhao & Maher, 1988; Gross & Do, 1995; Davies et al., 2009] and using the what-why-how framework and functional abstraction to understand how natural analogies can be applied to a given design problem, as well as analyzing the analogy for potential inconsistencies. This occurs repeatedly during their design projects, formalized in a number of activities, both as individual and as team assignments. In one exercise, students receive a number of engineering design challenges and are given the goal of developing these as analogous questions in a biological context. Another occurs as part of the design project, where each student must present to their group at least three biological systems that they believe represent appropriate analogies to their problem before they develop their final design. The group then chooses the five most appropriate analogies as a beginning of their design process (see next section).

Research assignments

Students practice finding and understanding research papers written on topics pertinent to their design projects, focused either on deepening their understanding of the problem they are investigating, or on enhancing their understanding of biological systems with functions that can be applied to their problem. Most students, even seniors have little knowledge of how to do this, so we provide an introduction to basic search techniques. This is essential if we expect student to be able to learn enough about biological systems, or how those differ from engineered systems with the same function. We focus on how to identify biological systems that are most like to solve the problem under consideration. That is, we discuss the idea of "model systems" as those most likely to have solved a particular challenge (e.g. desert animals excel at water retention). We point out that some of these principles can be abstracted (e.g. from cooling to thermoregulation) or inverted (e.g. from water conservation to channeling excess water) to broaden the search space. We also find that discipline specific terminology is a barrier to effective search, and that effective searching requires us to develop methods allowing students to relate terms in one field to those in another. For instance, biologists often use context dependent terms that relate to environment or the ecological value of a particular function rather than a more mechanistically precise term used by engineers. Accordingly, we encourage students to consult high level general sources first, and then "drill down" into the literature for more detailed analysis, which helps identify key biological terms that may be associated with the particular function or problem under consideration. [Chiu and Shu, 2007] show the utility of a more formal strategy based on the same idea.

Student research exercises are associated with their research project (described more fully below), where each student must bring multiple papers to the group, each of which describes a potentially different solution principle. This prevents the students from becoming fixated on particular ideas before they survey the diversity of principles that may contribute to a design. Because students discuss these papers in their group using the WWH format, they also gain practice in interdisciplinary communication.

Interdisciplinary collaboration

These student groups form the core unit for the various class activities referred to above. Students self-assemble into interdisciplinary teams based on common interest within the first few weeks of class, although instructors may modify team composition to ensure proper engineer/biologist balance. We strive for a diversity of engineering disciplines and at least 2 individuals well versed in biology.

The group is the focal point for most of the formal assignments. Research findings are first presented in the group, for instance, as are found object and analogy building activities. This facilitates our goals of knowledge acquisition and interdisciplinary communication. The ongoing efforts of this group are to produce a conceptual design (complete with a preliminary, quantitative assessment of feasibility) for a given biologically-inspired device or process. Students are asked for three iterations on their design during the semester. This iteration provides students with essential feedback that requires students to continuously reassess their ideas and requires to students to seek new analogies from natural systems. We use experts with appropriate specializations to mentor teams to facilitate and refine their 'search image' during their project phase, and teams are required to meet with them to vet design ideas.

The final design requires feasibility assessment and quantitative analysis, and we find that this requirement in the later stages when designs mature leads to more satisfactory results than purely conceptual design. Students are provided an opportunity to share the early iterations and design ideas during multiple mini-presentations and midterm poster sessions and final class presentations, facilitating information sharing across teams [NAS 2005]. This open-ended, project-based exercise requires students to incorporate all the lessons they have previously learned and encapsulates all the learning goals established for this class.

Idea Journals and Reflections

Students keep individual hard-copy idea journals throughout the course, and are asked to reflect upon the evolution of their thinking at the end of the course experience. The journals include text based reflections, as well as hand-drawn illustrations, printed pictures, and even biological found objects such as leaves and flowers. The act of reflection deepens students' understanding across all aspects of the class [Schoen, 1983; Anthony et al., 2007; Purcell and Gero, 1996]. These journals also supply valuable student feedback that can be used to assess the course.

TIME LINE/COURSE FLOW

Our 15 week course is organized to present initial concepts regarding BID methodology and practice during weeks 1-4, combined with structured in-course time to apply and discuss these concepts (**Figure 1**). This organization is designed with the following goals in mind: 1) allow students to develop the necessary inter-disciplinary communication and research skills to facilitate their design project work; 2) expose students to ideation and design skills that will encourage them to work outside of their comfort zone; 3) practice the analogical reasoning skills that facilitate the successful search for and application of relevant biological concepts.

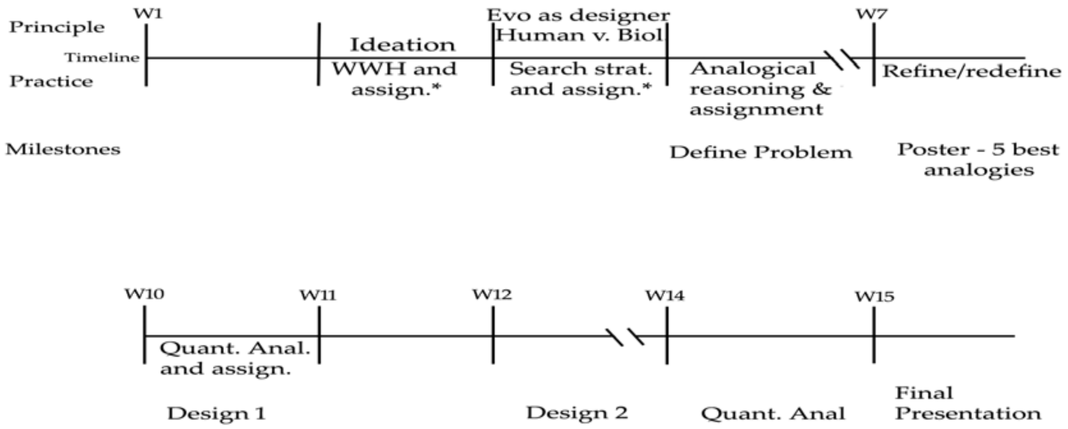

Figure 1: Weekly time line of course activities

Each division of the time line lists key components, broken up into Principle, Practice and Milestones. Principle refers to content normally presented via lecture activities, Practice refers to activities involving mostly class or group discussions, and Milestones represent significant assignment deadlines associated with the design project. Topical lectures on BID case studies, combined with corresponding found object exercises on the same topic occur in weeks (week number = W#) in which no activities are explicitly presented.

Students assemble into groups of 5-6 individuals in week 2 (W2), subject to the considerations of balance and diversify discussed above. Early assignments on analogical reasoning, search strategies, etc. are based on the initial interests of the students. Students define their central problem in W4 and thereafter, and most of the Milestones revolve around this topic.

Because BID often involves identifying relevant principles that may not be immediately obvious, we encourage students to take a broadly comparative approach early on, and seek breadth rather than depth at this stage. A common problem in engineering education is that students feel pressure to come up with solutions quickly, and are uncomfortable with ambiguity or uncertainty. In the BID process, we intentionally destabilize their thought process, asking them not to settle on their first solution and instead, engage in a comparative approach. Kazerounian and Foley (2007) state that ambiguity enhances creative thought and we agree with their findings. Thus, the first project milestone beyond defining their specific challenge is to mine the biological literature for what they consider the five best potential systems (analogies) for their challenge. The previous assignments in literature searching (W3), analogical reasoning and problem decomposition (W2, 4), and the ongoing found object exercises are all designed to prepare them for this task. Students present their initial problem decomposition and analogies in a poster session in W7, where they receive feedback from instructors, expert facilitators, and other students.

Preliminary project designs are presented in W10 and W12 as mini-presentations. This involves detailed problem decomposition and how the proposed solution maps on to this problem (see Section D.2.). The design in W12 is not simply a refinement of that in W10-it requires that students apply a new concept from a different biological principle. This encourages students to not be fixated on particular design ideas before they have a chance to explore multiple potential solutions. The quantitative analysis milestone assures that students have used quantitative reasoning to assess the potential feasibility of their solutions in light of the problem constraints, and is focused on the examining whether their solution can perform the appropriate function it is designed to achieve. The final project presentation includes an oral presentation as part of a course-wide design charrette (where we invite project mentors and outside experts as appropriate) and written summary as part of the evaluation and for guidance in the preparation of the final written report.

Below we describe, in more detail, some of the assignments that we believe are essential to prepare students for their design project.

EVOLUTION VERSUS DESIGN

To document the richness of design present in natural systems, one of our first lessons focus on the process of evolution and natural selection. This is followed by a series of comparisons that document the similarities and differences between natural and human made designs.

Evolution as Designer: Pitfalls and Opportunities

Biologists frequently speak of the design of organisms as a way to discuss biological functions that help animals survive. Engineers also understand design and function. The use and analysis of function provides strong link between biology and engineering. However, the evolutionary process that leads to biological functions (i.e. biological designs) is unfamiliar to many engineers, and promoting successful biologically-inspired designs requires knowledge about the basic features of evolution [Vogel, 1998].

Our discussion of evolution focuses on a number of separate but interrelated considerations. Our major points are: 1) Evolution is a chance process so a given function may have evolved through several different underlying mechanisms. For example-modifications to the cichlid jaw structure that confer high mechanical advantage are accomplished through a variety of genetic changes that alter different jaw bones; 2) Evolution increases fitness only locally, because constraints on what is possible (animals are not infinitely plastic) may limit available options. Thus, animals may only evolve a good solution, as opposed to the best solution. 3) Evolution is a historical process. Related organisms may share particular solutions not because it is the best, or the only solution, but simply because these traits are passed on from ancestor to descendent. Many crustaceans for instance, share common elements in their visual processing system because they are descendent from a common ancestor. 4) Closely related species in a group often have ecological niches that are largely similar, but which exhibit subtle but important differences relating to the specific expression of a given function. All bats, for instance, use echolocation for critical tasks, yet inhabit different acoustic environments that are important constraints on their acoustic detection systems, and 5) Evolutionary “design” operates on the level of the individual, not necessarily a specific function or sub-system. Thus, a given structure or process in biology may be the product of multiple, sometimes conflicting demands or constraints. This sometimes differs from human technology, where we often choose to build very specific solutions.

These principles imply some important things to keep in mind when searching for, and examining natural principles. First, biological principles will not be useful unless there is an analogous problem that requires evolutionary adaptation. Second, one must have a firm understanding of the appropriate level at which to interrogate a biological system, multiple pathways may lead to the same functional properties. Too narrow a focus may be misleading by identifying specific ways a problem may be solved rather than the unifying principle. Third, the appropriate goal of examining a biological principle may not be to find the optimal, but to establish a general principle that can implemented in a particular way that is best for a given technological problem. Fourth, the nature of historical constraints in biological systems means that literature search strategies must include comparisons across groups that are less likely to share solutions because of common descent. This strategy will be best for identifying robust principles. Thereafter, comparing across groups of animals that are related (e.g. species within a genus) may reveal how solutions are fine tuned for very specific challenges-that is, parameter values for system properties that are maximally beneficial for a given specific set of constraints.

We conclude with a short discussion of “evolutionary” constraints in a common device-the QWERTY keyboard. As chronicled in a number of different analyses [Noyes, 1998], the present incarnation of QWERTY is the result of many of the same phenomenon we discuss in the context of biological evolution, including historical constraint, competing design requirements, and incremental change. Feeding back from engineering into biology helps solidify the concepts and strengthens the link between the engineering and biological domains.

Once students begin to understand the complications and advantages arising from using the result of evolutionary processes as sources of design principles, they are ready to appreciate how natural solutions may be different from solutions devised by humans. We have developed an exercise that makes students aware of the differences between natural and technological approaches to problems as a prelude for their immersion into specific BID projects. Our goals are threefold: 1) make students aware of how differently biological processes "solve" particular problems as a way to enlarge the design space; 2) identify general principles used by biological processes, and reinforce the necessity to understand those processes before engaging in BID; and 3) reinforce some of the potential problems in transferring principles from the biological to the technological domain. Appropriate mapping of biologically based solutions onto technological challenges requires understanding constraints, which may be so dissimilar as to prevent application. By example, many properties of biological materials depend (at least partially) on hierarchy, but constructing hierarchically organized materials seems technologically challenging as it often may require control of materials at nano- and microscales, which is pushing the limits of many of our manufacturing processes.

The general goals for this exercise are to give students practice in recognizing natural principles, to distinguish differences between natural principles and principles used in human technology, and consider constraints. To encourage this practice among our student, examples of human and natural solutions are presented together via a series of paired images without instructor comment. Students are asked to compare and contrast what they see as relevant problem solving principles. The exercise concludes by revisiting each image pair and discussing the student's impressions. Because neither the problems nor the solutions are explicitly identified, this exercise allows students to practice problem-solution mapping, which is an essential skill required to identify and translate principles across domains. It asks them to consider both differences and similarities, which helps to sharpen their ideas on novel principles in the biological domain and where or why they arise. We are particularly careful to emphasize the range of biological processes that may act as inspiration, going from individual materials, to organ and organism levels (e.g. biomechanics, physiology), to single and multi-species aggregations. Students intuitively grasp the potential for translating principles derived from lower levels (e.g. materials, biomechanics), possibly because of the physical manifestation of the problems on these levels. Problems and principles on system levels seem more abstract, and may be harder for the students to identify.

ANALOGY EXERCISES

In practice, BID is a technique for complex problem solving using analogical design, where novel designs in one domain (engineering, architecture, etc.) are created by drawing upon solutions and patterns in the different domain of [e.g. biology; Bar-Cohen, 2006; Benyus, 1997]. Recent research on design, especially creative design, has explored the use of analogies in proposing solutions to design problems in the conceptual phase of the design process [e.g., Qian and Gero, 1996; Goel, 1997; Goel and Bhatta, 2004; Zhao & Maher, 1988; Casakin & Goldschmidt, 1999; Gross & Do, 1995; Mostow, 1989; Davies et al., 2009]. Recognition of BID as a process of analogical transfer has also led to computational tools for supporting biologically inspired design [Chakrabarti et al., 2005].

BID remains cognitively challenging despite the advancement of relevant theories and supporting tools. The process of making appropriate across-domain analogies is incompletely understood, and is a complicated effort involving the ability to break down a problem into discrete sub-problems, retrieving information about this sub-problem, and matching this solution to a the original problem. We find that errors in all of these steps are common stumbling blocks in the generation of successful biologically-inspired designs. Despite the importance of this process for BID, a detailed discussion of our efforts here are beyond the scope of this paper. As noted above, a number of accounts of this process are available. In addition, we provide, in a companion paper, a comprehensive account of how we use analogy exercises in BID and our findings regarding patterns of analogical design reasoning in our classes.

STUDENT REACTIONS

As mentioned, the overarching goal is to teach a systematic biologically inspired design approach by emphasizing a series of five learning goals that we believe are essential for the successful transference of biological principles to human design challenges. Below we share the results of our studies, as well as student feedback that is relevant to the assessment of our pedagogical practice.

Novel techniques for creativity

One of the driving goals for biologically inspired design is the increased attribution of creativity to biologically inspired designs. We know that analogy use and design fixation present significant challenges to students in biologically inspired design. With respect to analogy use, for a single design project we found that students investigate between 2 and 30 different cross domain analogies, and roughly half of the projects include more than one cross domain analogy in their final design solution [Helms et al., 2007]. The way these analogies are used in practice led the cognitive scientists to the development of a theory of compound analogical design (as presented in Section D.2.). With respect to design fixation, despite the requirement to investigate many design alternatives, as many as 66% of design projects use variations on initial design for their final design project, and only between one and three design variations are ever explored during the process [Helms et al., 2008b]. In response to this study of the 2007 iteration of the class, we added the requirements that students find 25 potential biological examples and work up 2 preliminary designs that use different principles.

Interdisciplinary communication skills

Most undergraduate students have limited exposure to working in design teams with students outside of their designated majors. Communication issues arise from multiple facets of these collaborations, including lexicon differences, discipline superiority biases, and representation preference differences, to name a few. In their reflections at the end of class, both engineers and biologists cite awareness of an expanded vocabulary and of a new ability to communicate across domains. The following quotes are direct excerpts from student reflections:

i) “I have also learned to communicate with those in other fields more effectively and hopefully to communicate with those in my own field more effectively.”

ii) “Working with two biologists in my group over the course of the semester though, I think I did learn how to better understand biological systems and speak in biological terms.”

iii) “…the most useful skill I learned this semester was learning to talk to engineers. For example, I had never heard of a stress-strain curve before, but I am happy to draw one for you now.

Knowledge about domains outside of core training

By definition, biologically inspired design requires knowledge about biology as well as knowledge of the core discipline in which the designers work, e.g. an engineering discipline, architecture, industrial design, etc. While students from one discipline are not expected to become experts in another, a level of basic engineering or biological concepts is necessary to facilitate interaction and contribution from all team members. In-class testing in 2008 shows 60-70% effectiveness for cross-domain transfer of basic domain concepts, which also is supported by the following student reflections.

i) Interactions and cooperation with the logical, calculating minds of engineering students have allowed me to learn how to look at a problem from a logical point of view, rather than the creative, ‘big picture’ perspective I often approach a challenge with.

ii) I know some biology majors, but interacting with them in this class really surprised me about how differently people in different majors think...It is surprising how specialized your thinking becomes after just two or three years without you realizing it.

The interdisciplinary design process

A key finding from our in situ cognitive study [Helms et al., 2007] is that approximately half of our students follow a solution-driven approach and fixate on an interesting biological mechanism, and then look for problems for which that mechanism is a good solution. This finding repeats itself consistently year after year. A number of reasons exist, but we observe that the need to understand biological principles in some depth may limit the student's ability to examine different systems. One of the key challenges reported in [Nelson, 2008] is the notion of sunk cost [Arkes and Blumer, 1985; Olds et al., 2005]. The implication is that time is a highly valued resource, and that after an investment in understanding an initial solution/design, students perceive too high a switching cost (in terms of time) to investigate alternative solutions. Nonetheless, student reflections also demonstrate a heightened appreciation for the complexities of the design process, and on the interdisciplinary nature of design:

i) I thought that the class was a good departure from the more traditional engineering courses, where formulas and methods are taught from a textbook and tested. While it is necessary that engineers are able to understand the basic disciplines…the ability to think creatively about real world situations seems to be a more important skill.

ii) Personally, I felt incredibly good about the outcome. I had never designed something of that caliber from start to finish; doing so was wonderful.

iii) This course has changed my perspective on the interactions between biology and design, and it continually altered and expanded my understanding of how to engage in successful design.

Application of knowledge across domains.

We struggle as educators to provide students with knowledge contextualized in a way that enables use of that knowledge outside of a classroom setting [Downey and Lucena, 2003; Bras, 2003; Norton, 2005]. As the following quotes exemplify, biologically inspired design provides a new context for the application of knowledge students already have.

i) "[This class] was the first class I've had that combined analogous biological phenomena to develop solutions for engineering problems. I could actually apply some of my knowledge in biology to real problems!"

ii) Along with a greater perspective on how engineering is applied to biology, I learned to think, brainstorm, and apply.

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