Chapter 7
Adaptive Evolution of Teaching Practices in Biologically Inspired Design

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Abstract At Georgia Tech in 2005, we developed an interdisciplinary undergraduate semester-long course, biologically inspired design (BID), co-taught each year by faculty from biology and engineering. The objective of this chapter is to share our teaching experience with those interested in teaching such a course themselves. The specific curriculum of a BID course must depend on the student mix, the institutional context, and instructor goals. Therefore, rather than presenting a particular curriculum, we present key problems that we encountered in our 8 years of teaching and how we addressed them. We expect that any who try to teach such a course will face one or more of the same challenges, and we offer numerous pedagogical approaches that can be tailored to their specific circumstances. By describing our solutions, their consequences, and the extent to which they met our expectations, we also point out where tough student challenges still exist that are in need of attention from the community.

Keywords Teaching biologically inspired design · Learning biologically inspired design · Problem-driven design · Solution-based design · Analogical design · Cross-domain analogy · Design by analogy · Understanding biological systems ·

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Functional decomposition · Structure-Behavior-Function · Design evaluation · Team design · Interdisciplinary design · Interdisciplinary education · Design creativity · Engineering design · Engineering creativity · Multi-disciplinarity · Team-based learning · Analogical reasoning

7.1 Introduction

Biologically Inspired design (BID) is highly interdisciplinary. The following four examples of BID illustrate the importance of contributions from different disciplines. For Velcro (see, for example, Simonton 2004), a close morphological examination of a plant burr provided the inspiration for a successful design of a fastener. For RHex (Altendorfer et al. 2001), a deep understanding of cockroach locomotion and stability of multi-legged organisms and robotic engineering was needed for success in an all terrain vehicle. The development of the Geckel wet adhesive (Lee et al. 2007) required a thorough understanding of the chemical and material properties of the biological solutions for gripping by geckos and sticking underwater by mussels. For the honeybee web-hosting algorithm, which dynamically allocates Web server resources to hosted services (Nakrani and Tovey 2007), the inventors needed mathematics to understand the bee behavior, the nectar output of flower patches, and the patterns of internet traffic. Thus, taken as a whole, BID spans science and engineering. Since few designers are likely to have deep enough knowledge in a wide range of fields required for any given design, BID often is collaborative. To teach a course well in this design paradigm likewise requires expertise in biology, engineering, and design.

At Georgia Tech in 2005, we developed an interdisciplinary undergraduate semester-long course [ME/ISyE/MSE/BME/BIOL 4740: BID] taught in the fall semester each year (Weissburg et al. 2010; Yen et al. 2010, 2011). The course recruits students from these majors: mechanical engineering, industrial and systems engineering, materials science engineering, biomedical engineering, and biology; in addition, we sometimes get majors from industrial design, architecture, chemistry, mathematics, or nuclear engineering. The course is co-taught by faculty from biology and engineering. Although it is not possible to teach deep knowledge in all these disciplines in a one-semester course, we can show the students that such knowledge can take them on the exciting path of BID. At Georgia Tech, we restrict this course to juniors and seniors who have established their majors, thus are able to bring specialized knowledge to the table. One of the goals of the course is to show the students how a deep understanding of their field and experience in working on an interdisciplinary team can enable them to be more inventive and creative. The goal is to motivate them to learn as much as they can in their field, then come to class to practice how to collaborate. In today's information-rich setting with easy access to knowledge resources, and in an increasingly interdisciplinary and collaborative design world, we turn our emphasis in this chapter on how to retrieve that knowledge, communicate it effectively across disciplines, and utilize it to solve problems in interdisciplinary teams. We think BID is a useful environment for learning and applying these skills.

In Yen et al. (2011), we defined the following five learning goals of the BID course: (1) Novel design techniques; (2) Interdisciplinary communication; (3) Science and Engineering knowledge outside core domain; (4) Interdisciplinary collaboration; and (5) Application of existing knowledge to a new field. To reach these goals, we presented the skills we taught, the exercises that we developed to enable the students to practice these skills, and the format of the class to indicate how we deployed these exercises. Our pedagogical techniques were grounded in the theory and practice of interdisciplinary research and education, recommended in the cognitive and learning sciences (e.g., Ausubel 2000; Bransford et al. 2000; Bybee 1997; Lave and Wenger 1991; Vygotsky 1978) as well as recommendations for teaching science (e.g., National Research Council 2011) and biology (e.g., National Research Council 2009). In Yen et al. (2011), we provided details on some of the more complex exercises such as biological design in natural evolution, problem decomposition, and analogical reasoning. We presented lessons learned from the first 3 years of teaching this course (2005–2007). To summarize, we found that creativity improved through the use of analogical reasoning to link biological functions to engineering challenges. We experienced clear differences in how biologists and engineers solve problems, which identified interdisciplinary communication gaps that were overcome, to some extent, by giving students practice in both domains in their interdisciplinary projects as well as by motivating them to apply their own knowledge to new problems and domains.

During the last 5 years (2008–2012), the BID course retained all the learning goals mentioned above. As this course and the field at large mature, additional challenges have arisen and become part of our learning objectives. In this chapter, we relay the triumphs and tribulations encountered in our ambitious plan to provide students with the opportunity to collaborate across disciplines through BID as well as learn about BID itself. The objective of this chapter is to share our teaching experience with those interested in teaching a BID course themselves. The curriculum of a BID course is flexible and depends on the student mix as well as the institutional context and instructor goals. Therefore, rather than presenting a specific curriculum, we present key problems that we encountered in the 8 years of teaching and how we addressed them. We expect that anyone who tries to teach such a course will face one or more of the same challenges, and we offer numerous pedagogical approaches that can be tailored to different circumstances. By describing our solutions, their consequences, and the extent to which they met our expectations, we also point out where tough student challenges still exist that are in need of attention from the community.

7.2 Key Challenges

While the inventory of skills required to generate successful BIDs is vast, we focus on the following key challenges that we see students struggle with year after year.

1. Searching for biological systems
2. Understanding biological systems
3. Identifying and understanding good design problems
4. Analogy mapping and transfer
5. Communicating across discipline boundaries
6. Communicating complex system knowledge
7. Teaming in an interdisciplinary environment
8. Maintaining equal engagement throughout the process
9. Evaluating designs

7.2.1 Searching for Biological Systems

In past studies (e.g., Vattam and Goel 2011), we have documented that up to 25% of out-of-class time can be spent simply searching for the right biological organism to solve a particular problem. While tremendous resources already are being devoted to solving this problem technologically (as this volume attests), currently students comb through volumes of textbooks, scientific databases, and the Web to find what they need. When they do find something promising: (a) it is often written in academic or technical language that is difficult for a non-expert to understand; (b) it takes time to determine whether it will be applicable to their design problem; and (c) it is usually not design oriented and requires translation before it is useful. These problems are magnified when the design teams do not have individuals with broad-based biological knowledge. Even when biologists are represented, they may not have the background that would be most desirable. For example, students with strong knowledge of basic organismal biology (e.g., comparative physiology, functional morphology, behavior, invertebrate and vertebrate biology) are the most well-equipped to search and identify appropriate systems for human-scale problems. Student designers typically (although not always) attempt to solve human-scale problems as this familiar scale is where humans have the most experience. For design problems at smaller or larger scales (e.g., at the molecular scale such as filtering pharmaceuticals from the water supply or at large scales such as city planning), different specializations may be helpful (from organic chemistry to ecosystem structure). Programs such as ours, where biologists are less well represented than engineers, require specific curricular elements to increase the ability of students to mine the biological literature.

7.2.2 Understanding Biological Systems

Our course has a mix of engineering, biology, architecture, and design students who must work as a team to understand the key mechanisms of the biological system so that they are capable of abstracting the mechanism and applying it to an engineering design problem. Whereas the biologists may have a deep understanding of a given biological phenomenon in its biological context, it is a challenge for them to communicate that understanding in such a way that the non-biologists understand it well enough to use in a design. This is exacerbated by the number and breadth of biological systems the students are asked to learn about, the limited time available for deep understanding, and the natural tendency of students to either focus on structural details, and/or use improper analogies to facilitate or communicate their understanding (e.g., the analogy: xylem in a tree acts like a straw in a drink—is not accurate at the mechanistic level since a pressure gradient is used to transport water by the straw while the molecular force of cohesion is used to transport water up to its leaves from its roots). Biologists who have experience examining biological systems in terms of function (e.g., biomechanics, physiology, and behavior) initially may be more able to communicate their understanding of biological systems in an appropriate manner. We find that architects and designers tend to focus on the structural elements of the system, at least initially, and require practice in thinking about function in biology. Engineers think about function, but generally lack the requisite biological knowledge.

7.2.3 Identifying and Understanding Good Design Problems

Throughout their scholastic careers, students are taught how to solve problems that are *given* to them. Less frequently faced in an academic context, this course presents a unique set of challenges when students are asked to identify and define a problem of their own choosing. Students in our BID class have (in early course iterations) devoted up to half the semester defining their design problem when challenged with a wide-open problem landscape. We have learned that BID may originate with the standard process of problem-driven design or may begin from a solution-based approach, where the unique mechanisms of a biological solution of interest determine which problems one may wish to explore (Helms et al. 2009). Thus, in solution-based design, problem identification is a critical aspect of BID. As instructors, we must balance the requirements of good problem identification and formulation against the needs of teaching a complete BID process.

7.2.4 Analogy Mapping and Transfer

Students often manifest cognitive limitations, biases, and errors (Helms et al. 2009). Whereas students naturally and effortlessly make analogies during the process of design, their analogies can be superficial. Students fall prey to a kind of confirmation bias, focusing on initial superficial alignment between analogue and problem, while ignoring deeper dissimilarities until they are forced to confront them late in the design process. For example, a student team in 2011 attempted to design a collapsible bicycle helmet inspired by the girdled lizard, which bends itself into a circle of spiked bands for protections against predators. The design failed because "protection" in the case of a bicycle helmet means dissipation and absorption of energy from a collision, whereas in the case of the lizard, it means resistance to penetration by claws or teeth.

7.2.5 Communicating Across Discipline Boundaries

Communication often is hampered by differences in the specialized terminology of different disciplines. For example, for biologists, "stress" represents extreme conditions such as heat, lack of water, or predators, to which organisms must respond using physiological, behavioral, genetic, developmental, or other mechanisms. For mechanical engineers, "stress" is the measure of force per unit area in a deformable body. Such differences occur even within the broad field of engineering, but become increasingly large as more disciplines participate.

7.2.6 Communicating Complex Systems Knowledge

In many disciplines, there are systems so complex that it seems impossible to draw possible analogies to another field without extensive research and teaching experience. We have found that decomposing a particular function of a system into subfunctions allows others to understand at least the interactions occurring at one level accurately even without gaining a full understanding of how all the functions in a complex system are integrated. If a subfunction still remains out of grasp of understanding, then it too must be decomposed further into its underlying mechanisms until a principle, common to both disciplines, is reached. This journey may take the designers several levels deep down in the hierarchical breakdown of the problem or the natural system, but success is more likely when the team reaches this common understanding.

7.2.7 Teaming in an Interdisciplinary Environment

Students taking classes within their field of study often work alone, or in teams with others in their field. Few if any entering students in our BID class have shared a course with someone outside their major. Hence, it may be difficult initially for students to recognize the value of knowledge and approaches outside their discipline. This can be abetted by the institutional persona that encourages divisions in the perceived utility of different fields of knowledge. For instance, engineers at a technology institute may think their expertise is more valuable than others. An appreciation for everyone's talent needs to be nurtured throughout the time the team is working toward a common goal.

7.2.8 Maintaining Equal Engagement Throughout the Process

The roles of each discipline may change throughout the course, depending on the stage in the design process and a design's specific requirements. Initially, emphasis is placed on biological knowledge since the teams have to select an organism and understand how the biological system works. Once the teams enter the design process, everyone is actively engaged because BID is unfamiliar to most students, with more weight placed on the biologists to find, understand, and explain solutions. The engineers are the most engaged when there is a required feasibility or performance assessment, work which biologists are not as experienced to perform. Under deadline pressure to complete a design, team members who cannot contribute directly can feel marginalized or devalued.

7.2.9 Evaluating Designs

A good design for our purposes must simultaneously satisfy the following criteria: functionality, potential market, manufacturability, novelty or competitive advantage, and reasonable cost. Although different ways of teaching BID may not emphasize all of these criteria, student designs become amorphous and speculative without a focus on functionality, novelty, and manufacturability, whereas failure to consider market and advantage results in designs that do not solve real problems or do so in a way little different from current designs. Challenges occur because: (a) students may not be familiar with using some of these criteria in their design analysis; (b) applying some of these criteria may require students to apply quantitative methods outside of their domain; and (c) students have trouble balancing conflicting criteria. These challenges are exacerbated by the profusion of possible quantitative analyses that could be performed. It is difficult for students to select the few analyses that are crucial.

7.3 Summary of Core Development Areas

In this work, we present our efforts to identify and solve problems in the teaching of BID, as embodied in the following five areas.

7.3.1 Content

In moving away from a lecture-based course to a problem-based collaborative learning environment, we need to balance between providing knowledge about biology, engineering, and design (content) and hands-on practice engaging in the BID process.

7.3.2 Representation and Tools

For students to find and learn about biological systems, to communicate that knowledge to people from different backgrounds, and to apply that learning to ill-defined engineering problems of their own making, we must equip them with tools that facilitate understanding and communication and focus attention on aspects of systems that are important for design.

7.3.3 Design Process

We have implemented several design process formalizations to contend with the special needs of a process focused on analogical design. As more experience is gained in teaching BID, we see similarities to and differences from more standardized design process approaches. One key difference is solution-based design: this process starts with solutions presented in natural biological systems and translates appropriate functions to solve design challenges in an inventive fashion.

7.3.4 Design Evaluation

Students produce conceptual designs in this course. Given the need to teach the process in 15 weeks, and the emphasis on student-identified design problems, building and testing a prototype to demonstrate feasibility is not possible. Nevertheless, even for conceptual designs, students must convince themselves, the class, and instructors that the design could work and would have some advantage over existing products. Throughout the semester, examples of quantitative analyses give students practice in addressing issues that often crop up in BID, such as scaling, materials selection, and environmental impact.

7.3.5 Interdisciplinary Teaming

BID can serve as a catalyst for innovation because of the mix of disciplines. But just throwing the students together would not lead to success. With different cultures, values, processes, and vocabularies, as well as different technical backgrounds, we have learned that a number of different teaming techniques are necessary to ensure proper communication, balance, and respect in a properly functioning team.

In the next sections, we document the challenges faced in each core development area.

7.4 Content

Given the multiple course objectives, balancing content is a difficult task. We must communicate a breadth of biology and engineering knowledge, accounts, and tools for design processes and facilitate interdisciplinary communication. Additionally, there must be sufficient time for the students to practice with the tools they have learned. We describe specific elements of content that we have identified to help meet those challenges and ways to maximize the effectiveness of this content to avoid overloading the students (Table 7.1).

7.4.1 BID Stories

To maintain student enthusiasm, we began every class with what we call a BID-wow story: an account about an exciting, innovative bioinspired design. These consist of examples such as: the whale fin inspired windmill blade (Miklosovic et al. 2004) which is more efficient, quieter, and able to capture wind energy at lower wind speeds; the slime mold that connected nutrient sources placed in a petri dish in the same pattern as major cities around Tokyo and grew a transport system as efficient as the Tokyo railway (Tero et al. 2010); the spacious, transparent cabins of the 2050 AirBus concept plane (http://www.airbus.com/innovation/future-by-airbus/) with a bionic structure mimicking bird bones to make planes lighter and stronger; the butterfly-inspired sensor that responds to different chemical vapors using the ordered arrays of iridescent scales to outperform existing nano-engineered photonic sensors (Potyrailo et al. 2007), or; the cat's eye retro reflector (Percy Shaw's patent No. 436,290 and 457,536) that reflects light back to its source with minimum scattering, similar to eye shine created by the tapetum of a cat's eye. These fascinating stories are told as soon as the class bell rings, encouraging the students to be in class on time, and keeping them focused

Table 7.1 Five course elements (down) pertaining to content that address the 9 key challenges (across)

Content	Searching for biological systems	Understanding biological systems	Identifying and understanding good design problems	Analogy mapping and transfer	Communicating across discipline boundaries	Communicating complex system knowledge	Teaming in an interdisciplinary environment	Maintaining equal engagement throughout the process	Evaluating designs
BID stories	X							X	
Case studies	X	X	X	X	X	X	X	X	X
Found objects	X	X			X	X		X	
Evolution	X	X							
Focused reading		X	X						

on the thrill of invention. While these news stories pop up frequently, they do not provide the details of the source of inspiration nor the process of transfer. For this, we turn to case studies.

7.4.2 Case Studies

Case studies presented by local experts provide information that can meet a variety of challenges from increasing subject knowledge to developing design skills and can be an integral part of any BID class. Locally, we have many to choose from, and the research described by familiar and respected teachers at one's home institute adds to the impact. Many of these bioinspired designs have taken years of research and development. As a result, the lectures given by the BID practitioners have a wealth of very detailed knowledge that students sometimes find difficult to absorb. Although the stories are all astounding and fascinating, what should/could a student get from this? One strategy is not to be concerned about content but to use these meetings to give the students the chance to meet and talk to the people behind the design, and we did that initially. We invited a parade of professors who used two of the 30 class periods (nearly 3 h in all), sharing their excitement about the process and product. This was great motivation, and students still rate these kinds of expert lectures as a favorite part of the class, but it did not teach the student "how to." Over the years, we reduced the number of lectures and the length (45 min plus time for discussion) and provided the following guidelines to the lecturer:

1. *Describe the key feature of the natural system that provided your inspiration.* In particular, we asked experts to focus on 3 things regarding their inspiration. What were the structures that come from the biological system? In this case, structure refers to the system components that perform the function of interest in the system. Why did this function help the organism survive? How did the organism achieve that function? This is the deep biological knowledge.
2. *Decompose the challenge you faced into its functions and describe the function that your design addressed.* What structures are needed for this function, what use is this function to humans, how do existing solutions achieve this function, and what are the limitations of existing solutions? This is the deep engineering knowledge.
3. *How did you translate the biology into the engineered design?* This is the design process. From this, we saw how analogical reasoning was a key element in this translation process.
4. *Provide the 3 best articles on your BID, one on the biological inspiration, one on the details of the specific biological mechanism of interest, and one on how the biological system were translated into an engineering design that worked.* This teaches the students how to read scientific literature.

This format is consistent with our emphasis on system components, interactions, and functions as tools to help students define effective analogies [see Sect. 7.6.6, Structure–Behavior–Function (SBF), and structured representation for BID (SR.BID)]. This narrative produces a balanced mix of both biological content and design process and leaves the students wanting to hear more about what the scientist–engineer did. There were always a handful of energetic students who asked a lot of good questions and we would have a lively discussion that spilled out into the hallway after class. One of the professors remarked: "I got more questions in this class than when I gave the same seminar to faculty and grad students in my discipline!" However, in our experience, these case studies (even when presented by an individual involved in the research) are not sufficient for the students to actually grasp the BID process, even when presented in the uniform way described above. Moreover, the journal readings and technical depth of the papers were clearly overloading the students with scientific publications that were difficult to read and understand. Despite this being a favorite activity of the students, we limit these lectures to 4–6 per semester, and instead, we focus on more hands-on learning strategies.

7.4.3 The Found Object Exercise

Observing, experimenting with, researching, and describing the functions of biological objects is a central curricular element that meets a variety of challenges, but is particularly well suited to increasing the ability to search biological systems and increasing interdisciplinary communication. Students are asked to go outside, find something in nature, play with it until something intriguing is noticed, then find an article that explains how the natural system works (Yen et al. 2011). Through this exercise, we want the students to reconnect with their natural surroundings, spend enough time interacting with nature to find something that is marvelous, and then deepen their knowledge by reading about it first in general biology/ecology/behavior texts that point to good articles. This develops a sense of connection to nature or biophilia (Wilson 1984). The objective of this part of the exercise is to figure out what search strategy to use to find the information needed for BID and how to get this information out of articles from the primary literature. We use their interaction with nature as the stimulus for deepening their biological knowledge base. In class, the team members share what they found and decide who has the best found object. That person tells the class about it using a succinct knowledge representation template (explained in the representations section). For a class of 40 with 8 interdisciplinary teams of 5, it takes the entire class period to do this. At the end, we review the 8 best objects and discuss whether enough was presented to understand how the system works. We found that when students became facile with the knowledge representation template, they could zero in on the key function of interest without getting caught up in all the other fascinating details inherent in complex biological entities. This helps the finders hone their analytical skills, focusing them on only the most salient features for design. This also helps the speakers to hone their communication skills, conveying the key principles that a biologist and an engineer need in order to see the value of the biological strategy of interest. Additionally, through active participation in the process, these exercises add a breadth of amazing local biological systems to each student's repertoire of biological knowledge, strengthening their appreciation for the local natural environment around them.

7.4.4 Perspective on Evolution

At the other end of the spectrum from the problem of providing sufficient depth, we have the problem of providing an overall perspective on BID. Engineering students can find the variety of biological organisms and functions to be bewildering. Biology students can have difficulty establishing and maintaining focus on biology in the context of design. We provide a lecture on evolution early in the course to help students gain a perspective on biology in the context of design. This lecture includes the concepts of common ancestry and convergent evolution, multi-function optimization, and local versus global optimization. This lecture has been given every year and receives consistently positive comments from students. It appears to help them understand differences between evolution as a design process and intentional design, which enables a more sophisticated view of how to search and evaluate potential biological solutions.

7.4.5 Focused Readings in BID

One of the nagging struggles of this design class is to provide the correct depth of information at the right time to students, and to do it without overburdening the students, or suppressing their motivation to continue reading throughout the course. Early iterations of the class asked students to find technical, academic papers for biological systems of interest. Considering that a student may do five found object assignments, five case study lectures, and must research up to ten biological systems, a requirement consisting of two documents per assignment results in a massive overload of technical documentation (up to 40 technical papers!). Adding requirements on top of the technical reading, such as formulating summaries or key questions for presenters only exacerbated the situation. The problem still remains: how do we ensure that students engaged in BID conduct deep explorations of a select few organisms, while getting a broad range of exposure to many and in such a way that given some biological system, they are capable of acquiring the knowledge on their own?

One means to address the breadth and depth issue was the use of a general purpose textbook, such as Vogel's (2000) Cat's Paws and Catapults, instead of technical papers prior to the case studies. The textbook is written to be broadly applicable, yet provides sufficient depth to highlight the key principles as well as the challenges of applying those principles. By aligning the themes in the textbook chapters with the themes of the case studies, we provide salient real-world examples to reinforce the reading.

The problem of finding and understanding deep technical references for a few systems, balanced against the need to understand, for example, found objects, remains an unsolved challenge in the class. Simply put, students give higher priority to generating exciting designs than to time-consuming deep reading.

7.5 Representations and Tools

As we have emphasized, BID requires students to find and learn about interesting biological systems, to communicate that knowledge to people with backgrounds different than their own, and to apply that learning to ill-defined engineering problems of their own choosing. In this fast-paced, novel context, students become easily overwhelmed and unable to identify clear learning objectives. Student presentations of biological systems found locally (found objects) in years 2006 and 2007 best exemplify these early struggles. When asked to summarize the most interesting aspects of found objects: (a) discussion is dominated by the structural details of biological objects; (b) students superficially associate a wide variety functions to the design; (c) though we emphasize mechanistic explanations, they are rarely provided; (d) if mechanistic explanations are offered, they are often provided by reference to a common sense analogy (often incorrectly); and (e) technical explanations employing terms from one domain are not understood by a majority of students from a different domain. In this context, what specific tools or representation strategies can help focus students on aspects of systems that are important for design? Table 7.2 below lists five that we have used in our course. In Sects. 7.4.1–7.4.4, we describe the first four. We postpone the description of the fifth, SR.BID, until Sect. 7.6.

7.5.1 Search Strategies

Since our initial classroom deployments, we realized that students are challenged with converting engineering-centric design problem language to the corresponding biological terms necessary to find biological systems in the external information environment. This is a particular problem when classes are dominated by engineers who have had little basic biology and are unfamiliar with potentially relevant biological systems. Starting in 2006, we offered three useful techniques for helping students to identify keywords that might lead to fruitful searches. These techniques are documented in (Yen et al. 2011), but in brief, we asked students to: (1) identify

Table 7.2 Four course elements (down) pertaining to representation and tools that address the 9 key challenges (across)

Representations and Tools	Searching for biological systems	Understanding biological systems	Identifying and understanding good design problems	Analogy mapping and transfer	Communicating across discipline boundaries	Communicating complex system knowledge	Teaming in an interdisciplinary environment	Maintaining equal engagement throughout the process	Evaluating designs
Search strategies	X								
SBF		X			X	X			
DANE and biologue	X	X		X		X			
Functional decomposition		X	X	X					

key functions of interest; (2), invert the function to reveal generic principles (e.g., heating and cooling both concern principles of heat transfer); and (3) identify extreme environments in which high-performing biological systems might be found. Each of these techniques provides one or more keywords that may be useful when browsing large collections of literature for biological systems. Regardless of the technique used, search remains challenging; students report that as much as a quarter of their design time is spent searching for information on biological organisms and functions (Vattam and Goel 2011).

7.5.2 Structure–Behavior–Function Analysis

As noted above, students have trouble articulating the properties and functions of biological systems in a way that facilitates abstraction and transfer of design principles. Our first iteration of this course in 2005 lacked any advice about representation, which diminished our ability to teach students how to transfer knowledge from one domain to the other. The basic problem is that both engineering and biological systems can be described in a variety of ways, which obscures the fundamental cognitive step of transferring biological mechanisms as solution principles.

In 2006, we introduced a single lecture on SBF analysis (Bhatta and Goel 1997; Goel et al. 2009), which is grounded in cognitive theories of systems thinking.

Structure–Behavior–Function

- Structure, behavior, and function form an abstraction hierarchy for systems thinking; behavior is an intermediate level of abstraction between structure and function.
- Structure specifies the components of the system as well as the connections among them. For example, the structure of the electrical circuit in an ordinary household flashlight comprises of an electrical battery, a light bulb, a switch, electrical connections among the battery, bulb and switch.
- Behaviors specify the causal processes occurring in the system. For example, the behavior of the flashlight is that when the switch on the flashlight is pressed, current flows from the battery to the bulb, and the bulb converts electrical into light energy.
- Functions specify the outcomes of the system. For example, the function of the flashlight is to produce light when the switch is pressed.
- Behaviors provide causal mechanistic explanations of how the structure of the system accomplishes its functions. For example, the behavior of the flashlight explains how its structure accomplishes its functions.
- A behavior of a system specifies the composition of the functions of its subsystems into the system functions. For example, the behavior of the flashlight composes the functions of its components—the battery, bulb, and switch—into the function of the flashlight.

- A subsystem or component of a complex system can itself comprise a system and thus have its own SBF model. Hence, SBF models of a system can have a hierarchical structure. For example, consider the system of the basilisk lizard, which is well known for its ability to run across water. If the function (F) of interest of the basilisk lizard is “run on top of water,” one can consider the opposing limbs, tail, and wide flat feet as part of the structural (S). The way in which the feet move in opposition are counter-balanced by the tail, and how the feet slap the water generating lift, then extend down and back creating more lift, thrust and a pocket of air in the water, and are then withdraw up and out through the air pocket could be considered the behavior (B) that generates the “run on top of water” function. One could consider the muscular-skeletal system of the legs as a subsystem of this system used to create a subfunction “generate movement of legs” which causes the higher-level “run on top of water” function. Likewise, one can consider the form the foot takes throughout the process as another subfunction, “change foot surface area.” In this way one can decompose the “run on top of water” function into a number of subfunctions, including “generate movement of legs” and “change foot surface area,” each of which could entail another SBF model. Similarly, one can consider the function “run on top of water” to be part of the function “escape predator” showing that one can navigate both up and down the levels of functional abstraction in the SBF model hierarchy. This kind of hierarchy will be discussed further in Sect. 7.5.4.

The origin of SBF analysis lies in Chandrasekaran’s functional representation scheme (Chandrasekaran 1994; Chandrasekaran et al. 1993). Other researchers have developed similar cognitively oriented approaches to thinking about complex systems, for example, Rasmussen (1985). Gero and Kannengeisser (2004) describe the design process itself in terms of function, behavior, and structure. Erden et al. (2008) provide a recent review of functional modeling. Note that in SBF analysis, functions are mental abstractions chosen by the modeler, and not intrinsic to the complex system. In the case of engineering systems, a functional abstraction corresponds to an intended output behavior of a system, subsystem, or component. However, since functions are mental abstractions, we can also use SBF modeling to model natural systems, including biological systems, such as the human heart, and ecological systems, such as forests. Even more so than engineered systems, natural systems exhibit layers of varied functionality at different scales, feedback loops, and other types of causal processes that characterize complex systems.

Recently, there has been considerable interest in the use of SBF modeling in science education. Goel et al. (1996) proposed the use of SBF models for explaining complex systems in science education. Ebert-May et al. (2010) and Speth et al. (2011) found that construction of SBF models in college-level courses helped expose students’ misconceptions of ecological and biological systems, respectively. Chan et al. (2010) found that high-achieving students in a college-level course on biomedical engineering paid more attention to behavior and function than did low-achieving students, and that attention to behavior and function improved student performance. Helms, Vattam and Goel (2011) found that SBF models of biological systems enable complex inferences that were not readily enabled by textual or diagrammatic representations of the systems. Vattam et al. (2011) discovered that use of SBF modeling for learning about ecosystems in middle school science classes resulted in statistically significant improvement in students' understanding of the structures, behaviors, and functions of aquatic ecosystems. Silk and Schunn (2008) summarize some of the benefits of SBF analysis in science education.

In 2007, we introduced SBF analysis as a framework for organizing found object exercises. Students were asked as part of the found object homework assignments (Sect. 7.4) and in their discussions to (a) focus on a single *function* of the organism in question, (b) identify the *structures* relevant to accomplishing that function, and (c) provide a *behavioral* explanation for how those structures give rise to the function. Instructors facilitated these discussions as necessary to guide students. (In the SBF vocabulary, behavior is synonymous with causal mechanistic explanation.)

As expected, students discussed structure at length, although they were unable to limit themselves to the discussion of a single function. As noted earlier, SBF is a hierarchical representation and systems are naturally functionally hierarchical. As a result, it was difficult for students to maintain a single level of functional abstraction during their discussions. Often students travelled "up" the functional hierarchy attempting to explain *why* the organism performed the function in question such as reproduction, survival, and escape from predators. The result was discussions about many high-level functions that lacked in detail. Less frequently, students travelled "down" the functional hierarchy, explaining a small portion of *how* the organism performed a function. These discussions usually resulted in very detailed, technical low-level discussions that only a few students could follow. One must continually emphasize to the students that, while the number of levels in a decomposition is very large, functions expressed at much lower or higher levels than the original problem may not always be useful for the purpose at hand, because they introduce constraints (lower levels) or goals (higher levels) not present in the initial problem definition. In addition to traversing levels of abstraction, students frequently confused the different senses of the word "behavior." Students often associate behavior with higher-level actions at the organism level, for example, mating behavior, territory marking behavior, seeking shelter from the heat rather than addressing the causal mechanisms, as this word is used in the cognitive sciences (Gero and Kannengeisser 2004; Goel et al. 2009).

To simplify the vocabulary, in 2008, we changed the SBF vocabulary to a What-Why-How vocabulary, mapping "What" to "Structure," "Why" to "Function," and "How" to "Behavior." This was an attempt to both remove the ambiguous interpretation of "behavior" and to formalize the levels of functional abstraction. Functional abstraction was considered in terms of "why" moving up the hierarchy (more abstract, superfunctions), and "how" moving down (more detailed, subfunctions). Again, students were asked to describe all biological systems in these terms, both conversationally and in formal homework assignments and design reports. Despite removing potentially confusing SBF language, students continued to describe these systems in a way that enabled them to avoid providing a mechanistic explanatory account. Table 7.3 gives an example from a midterm presentation in 2008.

It is illuminating to characterize the failure in Table 7.3 as a traversal in hierarchical levels. A *hierarchical level* corresponds to the vertical location of a function in a problem decomposition. Going down one level means to think about the subfunctions of the function under focus. Going up one level is to consider to what the focal function directly contributes. For example, if irrigation is the focal function, then acquiring, transporting, and dripping or spraying water would be subfunctions one level below. Sustaining plant growth would be a function one level higher, perhaps at the same level as harvesting; feeding the hungry would be a function considerably higher in the hierarchy.

In the case shown in Table 7.3, we see “What” addressing a function, “Why” addressing a higher-level function, and “How” addressing a structure, in this case color patterns. However, ideally, the “What” would address the components of the solution (e.g., structural color patterns), the “Why” would address the functions of solar absorbance and energy capture, and the “How” would explain the mechanism by which structural color patterns cause solar absorbance and energy capture.

The example in Table 7.3 uses “Why” to capture a function several hierarchical levels higher than the one that is really being considered. That is, while maintaining body temperature may be the top-level function or goal, it is several levels displaced from energy absorbance. This suggests an overloading of the term “Why” as both “the function of interest” and “the reason for the function of interest.”

In our experience, students need a large amount of practice with these representations to employ them correctly. As a rule of thumb, we have found that restricting the analysis to one to three hierarchical levels above or below the “What” function is useful to focus the student’s attention on the right structures, functions, and mechanisms. Levels above this cutoff often take the students to the ultimate evolutionary objective of a given biological “solution,” which may not match the engineering problem for which a given function may be useful. For example, the ultimate evolutionary objective, to survive, is so universal that it gives no additional guidance in the search for connections between biology and engineering. Going too many levels down may introduce constraints specific to the particular way the biological function is achieved, and which may not be relevant if the goal is to abstract the function rather than copy precisely the mechanism.

Table 7.3 Using What–Why–How vocabulary fails to generate a mechanistic explanatory account

Iridescent butterfly wings	
“What”	Solar absorbance and energy capture
“Why”	To maintain body temperature
“How”	Structural color patterns

Despite student problems with correctly identifying answers to the "why," "how," and "what" questions, we have found the SBF schema helpful because it helps students ask useful questions in trying to understand complex biological systems. Such hierarchical analysis is used to decompose complex concepts into manageable pieces of information. Thus, SBF has become part of the language of discourse in the BID class.

7.5.3 DANE and Biologue

We also have experimented with interactive tools that use SBF models to help enhance student understanding of biological and engineering systems. Given the importance of knowledge representations and interactive tools, it is not surprising that recently there has been enormous amount of work on devising representations and tools to support BID (Biomimicry 3.8 Institute 2008, 2009; Bruck et al. 2007; Chakrabarti et al. 2005; Chakrabarti and Shu 2010; Cheong et al. 2011; Chiu and Shu 2007a, b; Nagel et al. 2008, 2010; Sarkar and Chakrabarti 2008; Sarkar et al. 2008; Sartori et al. 2010; Shu 2010). These tools differ in their representations of biological and engineering designs, strategies for searching for a biological solution potentially relevant to a design problem, the (implied) process of BID, evaluation of design solutions, and so on. However, these representations and tools for BID are normative and prescriptive. We believe that it is important to situate the development of representations and tools in real-life contexts. The BID course has provided a motivation and a context for using, often in new ways, existing knowledge representations such as SBF, and also for developing and evaluating new representations such as SR.BID (see Sect. 7.6.6) and new interactive tools such as DANE (Goel et al. 2012; Vattam et al. 2010b) and Biologue (Vattam and Goel 2011) (see below).

DANE provides a digital library of SBF models of biological and engineering systems, as well as tools for constructing SBF models of new systems. We introduced DANE into the BID class in 2009. Some students in the BID class found DANE useful for making sense of complex biological systems and constructing a conceptual understanding of the systems. (DANE can be downloaded from <http://dilab.cc.gatech.edu/dane/>.)

Biologue enables students to annotate and share documents on biological systems as a team, to tag the documents with SBF models, and to search for additional documents based on SBF tags. We introduced Biologue into the BID class in 2012. Some students in the BID class found Biologue useful for online annotation and sharing of biology articles. In controlled experiments, we discovered that Biologue enables subjects to more easily and accurately locate relevant biology documents online (Vattam and Goel 2011). While initial results from DANE and Biologue are promising, identifying ways to search for interdisciplinary analogies remains an open research area (as this volume attests).

7.5.4 Functional Decomposition

In addition to the SBF analysis introduced in 2007, we began introducing decomposition diagrams in the class. Our early cognitive studies (Vattam et al. 2007) provided some evidence that analogical matching between problems and biological solutions was taking place functionally, but implicitly so. That is to say, we had no formal method of determining the quality of a match between the problem and the biological solution identified to help solve it. If we could formalize the decomposition of both problem and solution functionality, we would provide a more formal method for making and evaluating the connection between problem and solution.

In 2007, we introduced functional decomposition (Dym and Brown 2012; French 1996; Pahl et al. 2007; Simon 1996). An interactive lecture on problem decomposition was provided where the class participated in a group decomposition exercise for designing a search and rescue vehicle that could walk on uneven and shifting surfaces, such as sand. Figure 7.1 shows the decomposition that was created interactively with students during that lecture. Assuming functional matching was the primary index used to retrieve biological solutions from memory, a diagram such as this should provide a number of functions, each of which may lead to an array of biological solutions that could be applied to solve one or more of the subfunctions identified. Thus, multiple biological solutions could be used in solving a single problem. This phenomenon, termed compound analogical design, is well documented in class (Helms et al. 2009; Vattam et al. 2010a, b).

Students were asked to provide similar “solution-neutral” decompositions of their problem for all presentations and reports, as well as to justify their analogies by matching the functions provided by a biological solution and the function in the decomposition. Figure 7.2 is a typical example of a student’s problem decomposition. We found students consistently tailor these decompositions to the biological, and sometimes technological, solutions that they are already considering. That is, the functions that appear in the functional decomposition are nearly always aligned directly with a system that the students are considering. It is unclear whether this is selective pruning of the decomposition so that there are no functions for which there is no solution, or whether the decomposition is a result of a bottom-up approach where students fit functions from solutions to the problem decomposition. This bottom-up composition suggests that functional decomposition of a problem is not only formed in a top-down manner, but also may be partially formulated based on the availability of solutions.

7.6 Design Process

Students in BID class are asked to invent their own design challenge and to generate a creative, biologically inspired conceptual design that solves that challenge.

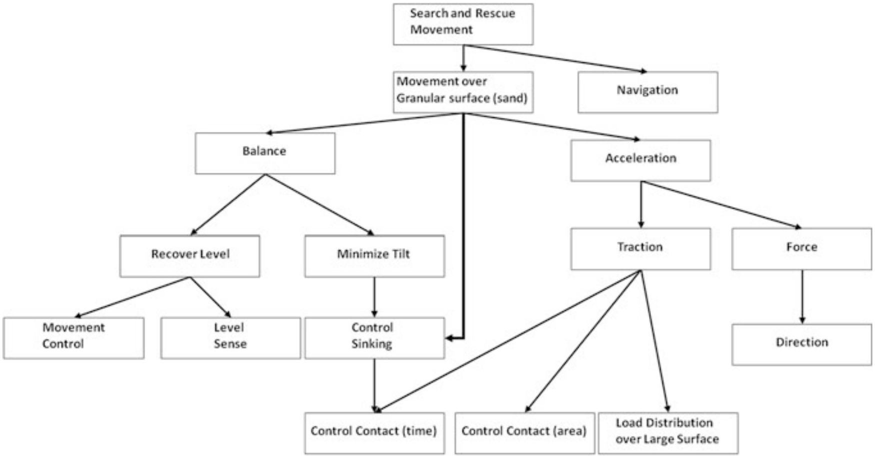

Fig. 7.1 Problem decomposition of a search and rescue vehicle to transport over uneven and unstable ground

Undergraduate students enrolling in a BID class may enter with little or no formal design process training. Even for engineering students, design is often in the context of a problem with very specific functional requirements, that is, the problem and evaluative criteria often are very clear. It is important to monitor the typical design experience of the student pool to determine how much to coach students through the process, particularly during problem definition.

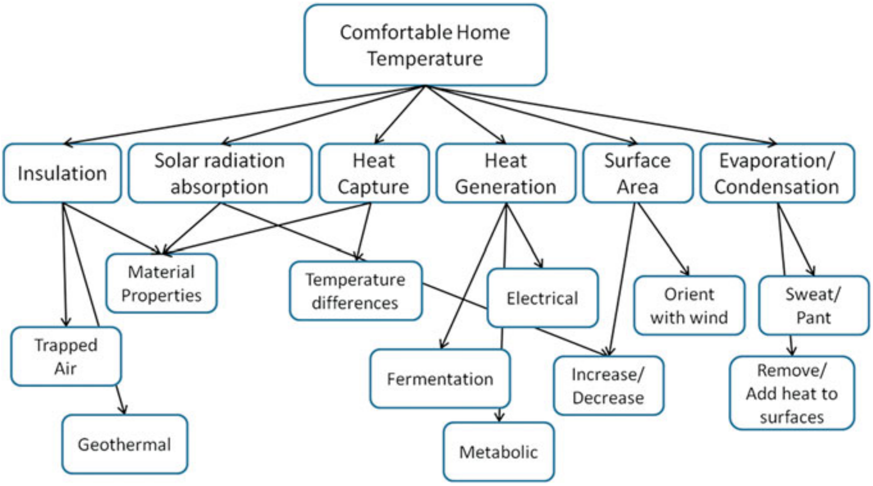

Fig. 7.2 Decomposition of the problem of maintaining a comfortable home temperature

Generating a new design problem, as well as learning a process for solving design problems adds an additional level of complexity to the design process. In early iterations of the class, we used a typical problem-driven design process, but we recognized that student designers spontaneously adopted a second design process, solution-based design. After close study of this process, we recognized that not only was the second process useful for students, but it also appeared to represent the more successful modern design approach outside of the classroom (Vattam et al. 2007). Beginning with the recognition that we needed to teach not one, but two design processes, we implemented a number of strategies for assisting students in structuring their design process (Table 7.4).

7.6.1 Problem-Driven and Solution-Based Design

Perhaps the most significant reworking of the class involved the organization of the class into sections representing these two dominant process modes for BID. Initially, we instructed students to find a problem, find a biological source, and apply the source to the problem to generate a solution. With regularity, half of the design teams would follow the problem-driven approach, and half of the design teams would instead fixate on an interesting biological solution and then find an appropriate problem to solve. Since each process seemed useful in different circumstances, we decided to formalize the different approaches and allow students to experience both.

On the very first day of class, students are now introduced to dozens of interesting biological systems in our "biology auction" exercise. The auction engages student's curiosity and imagination with a wide range of possible biological systems that can serve as design inspiration, either directly or indirectly. In addition, the immediate emphasis on biological systems reinforces the validity of biological knowledge and engages the biologists.

Over the next 6 weeks of the class, students identify one interesting biological system and figure out a means for using the interesting principles of that solution to solve a human-scale problem. We teach this process in class more formally as solution-based design and scaffold the process with exercises meant to help students (a) understand the mechanism of interest in their biological system, (b) abstract the mechanism used in their system, (c) identify a number of problems for which their system may provide a solution, and (d) formally analyze the analogy between their system and the problems they propose to solve in order to identify the best solution-problem match. Only in weeks five and six are students asked to begin producing conceptual designs.

We institute a more compressed problem-driven design cycle during weeks seven through ten. This begins with students: (a) defining a problem; (b) abstracting the problem; (c) finding biological solutions to the abstract problem; and (d) formally analyzing the analogy between their problem and the solutions they propose will solve their problem. Students craft a design solution in the last

Table 7.4 Six course elements (down) pertaining to the design process that address the 9 key challenges (across)

Design process	Searching for biological systems	Understanding biological systems	Identifying and understanding good design problems	Analogy mapping and transfer	Communicating across discipline boundaries	Communicating complex system knowledge	Teaming in an interdisciplinary environment	Maintaining equal engagement throughout the process	Design evaluation
Problem-driven and solution-based processes									
Source breadth	X								
Problem definition			X						
Problem focus		X	X		X				
Project format									
Analogical evaluation and SR.BID				X	X	X			X

week of this second cycle. This process of problem-driven design is an instantiation of the more basic cognitive process of analogical reasoning (Clement 2008; Dunbar 2001; Gentner 1983; Gick and Holyoak 1983; Goel 1997; Hofstadter 1996; Holyoak and Thagard 1995; Keane 1988; Kolodner 1993; Nersessian 2008). Solution-based design appears new and different from the perspective of design theory, all of which is problem-driven (e.g., Dym and Brown 2012; French 1996; Pahl and Beitz 1996). Thus, the BID course acts as a research laboratory for developing, identifying, and studying new BID constructs and processes.

With the remaining time, we allow students to continue to develop their ideas for either the first or second project. This allows students to experience both solution-based and problem-driven processes, while balancing the need to get deep into the design, permitting students to deal with the complex problems that come with more detailed design.

7.6.2 Source Breadth

The challenges associated with defining a problem, and finding and understanding biological systems, often result in students exploring few potential biological solutions (Wilson et al. 2010). This compounds the tendency of all novices to engage in design fixation. Students in early iterations of the course were required to explore only one problem and solve the problem with one or more biological solutions. Student designers in this environment investigated between two and ten biological solutions, while applying one or two biologically inspired mechanisms to solve the problem. However, in about two-thirds of the design projects, students fixated on the first biological system they encountered and only superficially explored other systems. Thus, in early classes student design teams shallowly investigated a handful of biological systems and came to deeply understand one or maybe two biological systems.

To counteract the effects of solution-fixation, student design teams are now required to report on at least thirty biological systems throughout the course. Each student examines a minimum of five biological sources before selecting one for their solution-based design, which means for a team of five, the entire team learns about 25 biological systems. These systems can be related to each other via convergent evolution, phylogeny, or exaptation. Furthermore, during problem-driven design, each student is required to report on five biological sources, or 25 natural systems for the team. In their final team design reports, a deep analysis is required of at least five of these systems. These systems may or may not overlap with systems discussed in their five found object exercises, again including up to twenty-five additional systems per team. Thus, student teams may explore and share knowledge about as many as *seventy-five biological systems* over the course of a semester. Furthermore, because students are trained in formally representing these systems using the function-based representation tools we provided (see Sect. 7.5), exploration of these systems is a structured process that (in theory) allows students to functionally index each system in their own memory for later retrieval during design episodes.

7.6.3 Problem Definition

In a semester-long design project, students (who again, are largely naive with respect to open-ended design problems) spend approximately half of the semester learning about and grappling with the complexity of their own design problems. Students seem to be motivated by tackling complex, often topical, issues such as oil-spill cleanup or eliminating traffic congestion, for which they may have little familiarity. In a class where students are expected to learn an incredible breadth of content and process knowledge, our task is motivating students to find interesting, challenging problems, without letting the definition of the problem itself become the core challenge.

Problem discovery and definition is usually the first step in the design cycle (Dym and Brown 2012; French 1996; Pahl et al. 2007). Even when the design cycle is solution-based, problem definition is quickly derived by working backward from a potential solution. Moreover, problem definition is inherently iterative. We have found, for example, that 70 % of the function requirements considered during the semester are discarded by the final design and as many as one-third of the final function requirements were identified during the final few weeks of a semester-long design.

We provide three scaffolds for students to help with problem definition. First, we give a lecture early in the semester that is inspired by Ron Bills, the CEO of Envirofit, entitled “What makes a problem a good problem?” this lecture provides an answer in terms of three W’s: what stinks, who cares, and what are you going to do about it? This lecture sticks in the students’ minds and keeps their focus on the practical. To reinforce this perspective, student design teams are required to answer the three W’s during their preliminary design evaluation. Second, we provide the problem-structuring tool (SR.BID) described in Sect. 7.6.6. These tools provide a handle for students to gain traction on defining their problems. Third, we embed problem definition formally in many of the design assignments, forcing students to reflect, to explicitly represent their design problems, and come to a shared team understanding of them. Our observations in 2011 suggest that these interventions: (a) reduce the time students spend on problem development; (b) reduce the problem scope; and (c) enhance the level of detail, especially with respect to the number of performance criteria and specifications that are considered. We believe projects in 2011 were among the most practical designs produced since we began teaching this class, with no sacrifice in perceived creativity.

7.6.4 Problem Focus

The extent to which student problems should be defined by the instructor versus by the students involves some trade-offs that may strongly affect student performance. We have tried limiting problems to specific areas (for example, sustainable housing) and allowing students to choose their own problems. Constraining student problems to specific areas potentially allows student groups to share information and come to a deeper understanding of the problem as a result of their joint efforts. It also may ameliorate some of the difficulties associated with problem formulation, and identifying and understanding biological systems. However, many students express disappointment that they were not allowed to choose problems with which they were comfortable. Moreover, constraining the problem sometimes limited the opportunity of certain engineering disciplines to participate. We also learned that unless problems are highly constrained, student teams were able to find a wide variety of problems such that benefits of shared knowledge were weakened considerably. Ultimately, in our highly interdisciplinary environment, allowing students to self-identify problems leads to stronger application of engineering knowledge and student motivation and is preferred even though problem definition remains challenging. Constraining problems to certain domains may be more productive when students share a greater amount of disciplinary knowledge or attitudes.

7.6.5 Project Format

The project format can serve a variety of goals, some of which may be important, but are ancillary to BID practice. For instance, it is common practice at Georgia Tech for instructors to require capstone design projects to be sponsored by industry partners, where industry partners then can participate in the project as real-world customers. We initially framed the project format in an entrepreneurial context, that is, student design teams were expected to pitch their designs to appeal to a group of venture capitalists. While students found this quite motivating, they also spent a lot of time on branding, marketing, and selling their concept, rather than understanding and articulating the underlying principles. Still, the emphasis on design feasibility is important. Thus, we currently frame the design process in a more pragmatic sense. We ask students to prepare a presentation that validates the design concept in a way that would convince us (the instructors, and other guest evaluators) to invest in creating a prototype of their design.

7.6.6 Analogical Evaluation and SR.BID

Since BID is a cross-domain activity between biology and engineering, analogy making is a cornerstone process of BID but formalizing instruction for analogical mapping continues to challenge us. Students asked to find a biological analogy for a problem like “create a device for collecting water samples at a fixed depth underwater in a lake,” can almost immediately produce answers like “puffer fish,” “pelican,” and “whale.” Remarkably, students generate these analogies naturally, without instruction, and within minutes given a particular design challenge. When asked to describe why the analogy is a good fit, however, students require much more time and often are at a loss for a description that they themselves find satisfactory. When asked to evaluate these analogies for applicability or “goodness of fit” for generating a solution to the design problem, students can often categorize one analogy as better than another, but they are generally incapable of producing a consistent rationale for why one is better than the other. These observations have led us to seek better ways to focus student attention on appropriate analogical mapping and evaluation of goodness of fit.

Students seem to use more than functional similarity as memory probes for arriving at appropriate analogies. Similarity of structure, external environment, and performance characteristics too are often involved; for instance, the search technique of “finding extreme adapters” is used to find high-performing biological solutions by environmental similarity of problem–solution pairs. Capitalizing on these findings, we introduced in 2011, a new representation framework called Structured Representation for Biologically Inspired Design (SR.BID) that extends and expands the SBF representation. The core aim of SR.BID was to create a comprehensive representation linking biological solution descriptions and problem descriptions over the broader range of concepts used for analogical indexing, mapping, and evaluation. The SR.BID framework borrowed the structure (called specifications in SR.BID) and function concepts from SBF, and appended environment and performance concepts noted earlier. The “Four Box Method” uses the four concepts pictured in Figure 7.3 to organize student thinking about problems and solutions.

Fig. 7.3 Four Box Method of SR.BID

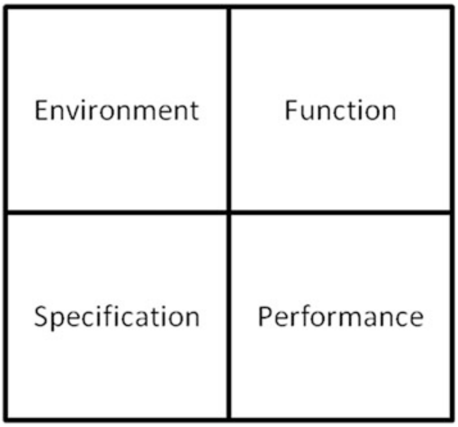

Table 7.5 Using the Four Box Method to describe the problem of building a better bike lock

Operating environment	Functions	Performance	Specifications
Outdoors and indoors	Protect bicycle from theft	Weigh less than 5 lbs.	Adjustable
Wind and precipitation	Prevent potential damage to bicycle caused by contact with lock	Withstand 4500 lbs. of force	Weatherproof
Daytime and nighttime		Withstand temperatures below 32° F and above 100° F	Flexible
Temperature variations		Waterproof, freeze proof, and shockproof	Strong materials
			Easy to use
			Deter from cutting
			Competitively priced

All assignments in the 2011 class were structured using the SR.BID framework. The following Table 7.5 provides an example of a four box diagram provided to describe the problem of building a better bicycle lock.

Furthermore, once given a problem specification and a specification of the biological solution in the same format, students were asked to do a side-by-side comparison where they identified whether elements were the same, similar, or different. In Table 7.6, we see a side-by-side comparison of the North American Elk antler with the bicycle lock problem. This side-by-side comparison forces students to consider not only where the problem and solution align, but also where solutions do not line up. Markman and Gentner (1993) have suggested that comparison of source and target problems in analogical transfer often is based on such alignment. We believe that in BID, highlighting these differences early in the analogical mapping stage helps students consider their sources more deeply, as well as identify potential transfer issues such as performance, size scaling, material composition, and manufacturing earlier in the design process.

From 2006 through 2011, we have experimented with a number of representations and tools to help students overcome common interdisciplinary design challenges. We have less experience with SR.BID than with other representations. However, student surveys indicate that the SR.BID organizational framework resulted in more pragmatic final projects and provided students with a more robust method for evaluating analogies, especially for identifying potential transfer failure points. On the other hand, students continued to provide shallow mechanistic explanations of biological systems. In 2011, we did not teach diagrammatic functional decomposition, and instructors felt as a result students lacked a deeper understanding of the connectedness of functions in both problem and solution descriptions.

Table 7.6 Side-by-side comparison of the biological solution (Elk antler) with the problem (bicycle lock) using SR.BID

Problem target		Biological source (Elk antler)
Operational environment		*Operational environment*
College students/adults	N/A	N/A
Global use in all habitats	Different	North America/Eastern Asia/forest habitat
Bike racks, poles, sign posts, fixed structures	Different	Elk head
Usable in all seasons/usable at all times of day	Different	Usable only during mating season
Temperature range: adaptable to outside temperature	Same	Temperature range: adaptable to outside temperature
Weather resistant	Same	Weather resistant
Functions		*Functions*
Prevent bike theft	N/A	Fight/protect against other male elks during mating season
Withstand applied stress	Same	Withstand applied stress
Maintain temperature	Same	Maintain temperature
Deter possible thieves	Similar	Deter predators
Specifications		*Specifications*
Stress withstanding materials	Same	Stress withstanding
Lightweight materials	Different	Strong materials
Inexpensive materials	Similar	Relatively low energy cost
Inert materials	Same	Inert materials
Detachable from bike	Similar	Ability to shed antlers after the end of mating season
Lifespan of over 5 years	Different	Lifespan equals the duration of mating season
Criteria		*Criteria*
Weight <5 pounds	Different	Weight of up to 40 pounds
Fits around average sized tree trunk	Different	Height of up to 3.9 feet
Fits on/around average sized bike frame	N/A	N/A

7.7 Evaluation

One of us once overheard an alumnus from our 3rd iteration of the course describe it to a prospective student. He said, “It’s different from any other course. There are assignments like ‘go outside and find something.’ It’s hard to know exactly what you’re supposed to do.” In most courses, it is clear to the students what specific information and skills they must master. Because BID education is process oriented, as opposed to content oriented, the students often have trouble gauging their own performance, particularly before their first projects are vetted. Evaluation by the faculty is necessary throughout, and most important quite early, to help students realize what it is they should be working on, how good their work is, and what mental activities are leading to productive outcomes. The first two course

Table 7.7 Six course elements (down) pertaining to evaluation that address the 9 key challenges (across)

Evaluation	Searching for biological systems	Understanding biological systems	Identifying and understanding good design problems	Analogy mapping and transfer	Communicating across discipline boundaries	Communicating complex system knowledge	Teaming in an interdisciplinary environment	Maintaining equal engagement throughout the process	Evaluating designs
Three W's			X		X		X	X	X
In-class feedback			X						X
Environmental impact assessment								X	X
Make-or-break QA									X
Materials assessment									X
Reports		X	X	X		X		X	X

elements in Table 7.7 below are the main methods we have found to get students on a productive track early in the course.

Ideas are commonplace; good ideas less so. Many of the ideas in the student journals were novel, but impossible to implement so as to achieve the desired functionality. Quantitative analysis is usually the key to assessing feasibility of a design. For example, how much must the surface area of a shoe expand to prevent sand from liquefying when an adult walks at normal speed? How much will serrations at the leading edge of a lawn mower blade reduce noise? Course elements 3–5 in Table 7.7 represent the quantitative assessments we require. In addition, we ask the students to perform some quantification of the three W's.

The last course element in Table 7.7 is the final report. This pulls together the biological sources, problem description, design description, analogical evaluation, and all of the quantitative analyses that are described in this and the previous sections. If the students can write a persuasive project summary and have correctly performed the underlying analysis, they can feel confident that they have delivered a good BID.

7.7.1 Three W's

The three W's, "What stinks," "Who cares," and "What are you going to do about it," were introduced in Sect. 7.6.3 as scaffolding for student problem definition. For the oral presentations of the first two projects, we require the students to state the three W's of their problem definition. This helps them select a worthwhile and well-defined problem. For the final reports, we also require quantitative justifications of each W. For example, the first W would ask how wasteful are lawn sprinklers compared with drip irrigation? The second W would ask how much clean water is wasted annually by lawn sprinklers and of what fraction of total clean water use does that consist? A more thorough answer to the second W would calculate the annual cost of the wasted water to a typical owner of a water sprinkler. If the annual cost is a few dollars, who is going to care, even if the overall cost is a hundred million? The third W would call for the quantitative analysis of the design to be sure it saves the amount of water claimed, and an estimate of the production cost.

7.7.2 In-class Feedback

During in-class work sessions, we circulate among groups, answering questions, critiquing designs, helping with analyses, and suggesting ideas. We have not kept records of these interactions, but we are sure that this feedback is indispensible to the students during the first and second design projects. We often have the ready knowledge to tell a group that an idea has already been tried, or that an organism's mechanism is not what they think it is, or that the basic nature of their problem is different from what they suppose. This kind of feedback helps eliminate dead ends early, before the team sinks much time into them.

The other kind of feedback that is very helpful during the early stages of work has to do with problem focus. Students frequently begin with too broad a problem and need to be advised to narrow their focus, often drastically. It has become much easier for us to provide this feedback now that we have taught the course for several years, because we have acquired some problem domain knowledge. For example, every year since 2006 at least one team has wanted to solve the problem of water. We have learned that worldwide water problems range from aquifer depletion, desertification, inefficient irrigation, and leaky toilets to collection, non-point-source pollution, filtration, and millions of children's deaths annually. Each of these differs by geographical region, culture, and other factors. We might suggest a focus on collecting potable water from the air for a hundred thousand refugees living in makeshift tents in Haiti, or on finding gray water alternatives to pure aquifer sources for farmers in the midwestern USA.

Occasionally, a group will have too narrow a problem focus. If their solution is good, it is usually enough to point out that there is not a sufficiently important "who cares," and urge the students to find a broader scope of application. Therefore, it is not usually vital to detect this flaw very early. Feedback during in-class presentations, discussed next, is sure to reveal such flaws that have not yet been detected.

We invite experts from various departments such as mechanical engineering, materials engineering, architecture, chemistry, psychology, and civil engineering, as well as local firms such as Perkins+Will, Interface, and David Oakey Designs and that are interested in sustainability, to attend the oral and poster presentations of the student projects. These presentations are typically given a week or two before the final project reports are due. Each team gets feedback from the visiting experts, the course instructors, and their fellow students. Surprisingly, we have found that some of the toughest questions come from other students. The visitors are the most likely to challenge fundamental assumptions or parameters of the entire project. We instructors, perhaps because we have been providing feedback all along, tend to ask the least unsettling questions. Instead, we usually probe to test whether or not the students have a deep understanding of the biologically inspired mechanism that is being transferred into the design.

Several times visitors have expressed regret that they had not been brought in earlier, because there is not enough time for the student team to act on their criticisms or ideas. On the other hand, these visitors are a scarce resource and we are leery of imposing too much on them. The best use of this resource seems to be during the presentations of the first and second designs, because the teams will choose one of those two to refine for their third design and therefore have several weeks to take an expert's comments into account.

7.7.3 Environmental Impact Assessment

Student responses to our course suggest that BID captures the imagination and attunes students to values of sustainability. In fact, many engineering students in our early courses reported they were more likely to consider sustainability and environmental impact of their designs as a consequence of learning BID, even though sustainability was not a design requirement. Subsequently, we added an environmental impact assessment (EIA) assignment to align student output with their greater sensitivity to environmental concerns.

The EIA assignment creates a number of challenges, given many engineering and biology curricula do not cover this kind of evaluation. We discovered it was necessary to familiarize students with the major environmental impact categories and their associated metrics (e.g., greenhouse gases in CO_2 kilogram equivalents and solid non-toxic waste in cubic feet). We identified some of the most common difficulties and created a quantitative homework assignment that forced the students to navigate them. The assignment was to compare the environmental impact of travel by air and travel by car. This forced students to understand the need to express the cost per function achieved (e.g., amount of CO_2 equivalents released per passenger miles travelled), and how to prioritize potential costs (e.g., the amount of clean water used per passenger mile is negligible compared to the impact of greenhouse gas emission). Afterward, when teams were working on their projects, we met with each group to discuss which impacts were important and how they were to be measured.

Several of the changes that we have described, namely identifying pitfalls and environmental impact categories in lectures, tailoring quantitative analysis assignments to these lectures, and discussing these issues with each team while they were developing their designs, had the net effect of changing quantitative assessment from a burdensome requirement of a final report to a key tool used during much of the design process.

7.7.4 Make-or-Break Quantitative Analysis

In the first three years of the course, we gave three quantitative homework assignments, each analysis tied to a specific reading or lecture. Our aim was to stimulate students to perform quantitative evaluations of their projects. These assignments were unpopular; many students, especially biologists, found them difficult. Starting in the fourth year, we changed these from individual to group assignments. To keep the biologists engaged, we offered extra credit to teams if a biologist presented the group's solution to the class. We observed that the quality of the student solutions improved, and that the student satisfaction with the assignments increased when the design team was jointly responsible for the exercise.

However, the degree to which all team members, in particular the biologists, learned how to do quantitative analysis is unknown.

Though we do not know whether everyone learned *how* to perform quantitative analysis, we do know that the students did not learn how to choose *what* quantitative analyses were worth doing. All final design reports were supposed to include a quantitative assessment that related to how well the design functioned. In the first few years, we were usually dissatisfied with their quality. Many assessments lacked depth or importance. Teams frequently analyzed aspects of the design that were not critical to its performance, choosing analyses with straightforward techniques as opposed to relevance. We elected to address this problem with a "make-or-break" lecture, in which we stress that usually there is a single quantitative issue *of function* that is critical to the success of the design. A bicycle helmet must be able to protect against a certain speed of collision; a condensation device for desert use must produce a certain amount of water per day; a levee must withstand a certain flood height. We told each team to figure out what would make or break their design. We then met with each team to discuss their choice. This discussion was important because otherwise a difficult time-consuming technical analysis could turn out to be irrelevant or a major design infeasibility could go undetected.

Our subsequent experience has led us to identify common issues that students confront in this analysis. One pitfall has to do with scaling. For example, a human-sized gecko could not climb walls easily because the mass increases as the cube of the length, but the surface area of the foot increases only as the square of the length. The adhesive force is proportional to the surface area, as a simple thought experiment will show. We created a new quantitative homework assignment for which scaling was the key. Since biological solutions often are scale-dependent, students often will have to deal with this issue, and some discussion of scaling seems key for successful analogical transfer of principles. The other common pitfall had to do with materials. This was so important that we made a materials assessment a separate requirement, as described in the next subsection.

7.7.5 Materials Assessment

Students in the first 3 years of the course would often base their design on a hypothesized material with certain physical properties, when no such material existed. When we reviewed the course after 3 years, we were a bit shocked to see that this single weakness rendered about one-third of all the designs infeasible! We began to warn students not to rely on imagined materials, encouraging them to use existing material or to design a hybrid material from known materials. Now, we require a materials analysis in the second or third week of the third project. The final reports typically incorporate this materials analysis.

Often the properties of a material have turned out to be the "make-or-break" quantitative question. In several cases, teams performed a computation-intensive finite-element analysis to answer the question. Usually, only one member of the team, a mechanical or materials engineer, knew how to perform such an analysis.

In our experience, therefore, a materials analysis seems necessary to prevent situations in which students produce unfeasible designs. In the most recent iteration of the course, fall 2012, only one of the eight final designs (a radically different toothbrush) depended on material of dubious manufacturability.

7.7.6 Reports

We have always required students to deliver both oral and written reports. In the first year, we tried different formats. For written reports, we asked for traditional write-ups of about 10 pages, posters, and pamphlets of 4–8 sides. For oral reports, we asked for either short poster presentations or PowerPoint presentations. We observed that students were highly motivated by poster presentations, and we have retained them. We found that written reports got much better if we specified a template in advance and tied all of the elements in the template to previous assignments. In this way, final reports served as a reflective synthesis of previous work and provided an opportunity for improvement. Report templates also provided students with focus. There are so many aspects of the process of BID that could be included in a report that students are at a loss for what to include or not include. In particular, in 2007, about 40 % of the final report documented the design process, while 60 % documented the actual final design. The template seemed to reinforce both the process learning goals for the students and the product/design goals. Creating good rubrics for a class is an extremely difficult problem, particularly in design. To grade the final designs, these 10 sections are awarded a specified portion (%) of the final grade as follows:

1. *Summary* (5 %). Specify the problem and the biological source; state the key analogy; describe the design solution and its value proposition as compared with existing solutions.
2. *Biological System Understanding* (10 %). For solution-based designs, convey a deep understanding of the primary natural system, with particular focus on explanation of the mechanism(s) of interest. For problem-based designs, provide a deep description of all mechanisms transferred to the design. In addition, describe at least briefly all natural systems that were considered, indicating why a system was or was not chosen for inspiration.
3. *Design Problem Understanding* (10 %). Motivate the problem, including what stinks, who cares, and what are we going to do about it. Also, give a detailed problem decomposition showing a logical analysis of the functions involved in the problem including function, operating environment, performance criteria, and constraints.
4. *Biological System to Design Problem Analogy and Comparison* (10 %). Describe similarities and differences between the biological systems and the

design problem. In addition, present arguments for and against the suitability of the biological systems to serve as a solution to the design problem.

5. *Visualization* (10 %). Supplement the written text with a variety of visual representations such as graphs, figures, drawings (CAD or freehand), and tables. Legends must be informative.
6. *Quantitative Analysis of Biological Mechanism* (20 %). Provide a succinct and quantitative analysis of the mechanics, material properties, or interacting processes of the biological system(s) that are transferred to the design.
7. *Quantitative Analysis of Design* (20 %). Provide a succinct and quantitative analysis of the key functions of the problem. Show how the new design integrates the principles derived from nature.
8. *Design Understanding* (10 %). Discuss the principal obstacles to achieving the design objectives that were encountered. Assess the value of the design (greater functionality, cost savings, increased sustainability, other potential applications).
9. *Cross-Domain Translation Creativity* (±10 %). This portion of the grade depends upon the creativity of the design based on its novelty with respect to current technology and previous BID designs, together with the potential usefulness of the proposed product.
10. *Literature* (5 %). This must contain key references from the primary literature (no Weblinks allowed) for the biological systems, existing solutions, similar problems, materials, and mechanics.

Item 9 in the list above requires clarification. The weights of the other items sum to 100 %. Item 9 permitted the project grade to go up or down by as much as a full level, for example, from B to A or C. We instructors did not fully agree as to how much the designs should be graded on the process rather than on the outcome. Item 9, being a highly subjective criterion, gave individual instructors leeway with respect to the rest of the grading rubric. To ensure fairness, we balanced the set of instructors assigned to each report. Note also that the weights assigned to these categories will vary, reflecting the instructors' course goals and institutional context.

In the most recent iteration of the course, we required a complete draft of the report a few weeks before the final version was due. We graded the drafts as carefully as we would have graded final versions. About half of the final reports were much improved over the drafts. (several were already excellent). This process required a lot of time from both faculty and students, but it significantly improved the outcome.

7.8 Interdisciplinary Training

Having the opportunity to work in interdisciplinary teams gives students that chance to examine a problem from a different viewpoint, share uncommon knowledge between disciplines, enable them to re-examine their own major, and in essence, seed their minds with new ideas. Teams in this class include at least one of each of these two disciplines: biologist, mechanical engineer, plus a mixture of these: systems engineer, materials scientist, designer (industrial designer, architect, and artist). Asking the students to show they are able to use each other's skills, starting from the biological inspiration, throughout the design process, to the final quantitative analysis of feasibility informs them of the importance of the interdisciplinary effort. These interactions expand their design space, promoting creative thinking and innovation in design (Table 7.8).

7.8.1 Faculty Engagement

How often does a biologist work on a team with a biomedical or mechanical engineer, a materials scientist, an industrial engineer or an architect or city planner? One key to effective bioinspired design is that it requires expertise in multiple fields. In our experience, there is no greater influence on the success of a final design than having a mentor to help facilitate the team design. Even one or two sessions with an expert can make a dramatic difference. For example, when a team of mechanical engineers, computer scientists, and biologists tried tackling the issue of desalination, they classified the problem as one of finding a way to generate water pressure for reverse osmosis. Having created a biology-based solution that required "no input energy," the team thought they had "solved" the problem. Five minutes with a faculty expert, and suddenly, now recast in terms of a thermodynamics problem, the team saw they had a major problem with their design (specifically that the system would quickly reach equilibrium after which no further desalination would occur). Over the years, we have identified those faculty who are open to interdisciplinary collaboration, can spare the time to facilitate a team over several one or 2 h sessions, and evaluate the output in such a way that makes sure the team correctly understands the principles of interest. Taking advantage of local expertise helps customize the course to the strengths of the institute.

7.8.2 Knowledge from Other Domains

As already mentioned, BID draws from many areas of scientific knowledge and cannot be accomplished without at least two or more disciplines working together. In our course, we emphasize the essential value of knowledge from other domains. In particular, it requires a sufficiently broad understanding of biology to facilitate search and selectively deep understanding once a particular biological source is targeted as a potential source for innovation. Whereas substitutes exist, there is still no resource quite as effective as *a good biologist*.

Table 7.8 Five course elements (down) pertaining to interdisciplinary training that address the 9 key challenges (across)

Interdisciplinary training	Searching for biological systems	Understanding biological systems	Identifying and understanding good design problems	Analogy mapping and transfer	Communicating Across discipline boundaries	Communicating complex system knowledge	Teaming in an interdisciplinary environment	Maintaining equal engagement throughout the process	Evaluating designs
Faculty engagement		X							
Knowledge from other domains	X	X	X	X	X	X	X	X	X
Nature auction		X			X			X	
ID teams					X		X		
Peer evaluations					X		X	X	

It is not easy for an engineer to identify keywords to search for a system with properties they seek: a BID thesaurus is useful, and biologists can act as a "translator." Although several groups are working on techniques, such as context-based searching, to help engineers bridge the knowledge gap without direct access to biological expertise, such an approach is neither optimal nor justified when there is easy access to biologists. Hence, we always place at least one biologist in a team of 5, although adding additional biologist team members, when possible, is sound practice. Just as for engineers, there are many kinds of biologists, so the particular ability of the biology teammate can affect strongly the choice of systems that can be examined by the team.

7.8.3 Nature Auction

It is important to emphasize the vital role of non-engineering disciplines in what is (ultimately) an engineering design exercise. One of our techniques is to throw the students into a fun but unfamiliar situation that establishes the importance of different types of knowledge. In our first class, we form temporary student teams, each containing at least one biologist. Then, we engage them in an extraordinary auction. *We are auctioning off nature.* The room is lined with often spectacular images of organisms (e.g., basilisk lizard) performing some uncanny feat (walk on water) with a caption that describes the behavior. The teams are given an equal number of "BID dollars" to select at least 3 (usually 4–5) biological systems to study for their first (solution-based) BID. They examine potential selections as a team and discuss the value of each natural system as the basis of their choice. Thus, begins the process of revaluing the role of nature, and the role of their fellow teammates! The BID auction not only provides them with a jumpstart on their investigation of interesting biological organisms, but also helps them learn about the knowledge, values, and perspectives of their teammates.

7.8.4 Interdisciplinary Teams

We continue to use the interdisciplinary team as a way to encourage the importance of acquiring and communicating knowledge outside of one's domain. In the final presentations, extra credit is given to the engineer who can explain the biological function and the biologist who can explain the engineering function. This embeds in each team the need for all participants to share their knowledge and is one of the pedagogical advantages of collaborative inquiry-based learning (Bransford et al. 2000; Bybee 1997). Eventually, everyone in the group understands the value of the biologist but usually, the biologist remains the source and search engine for interesting biological strategies. Similarly, not all the biologists succeed in becoming a materials engineer or mechanical engineer, but often understand the basic constraints and capabilities of these skills, and learn how to express themselves using concepts familiar to the engineers. All students come to the conclusion that they can address this complex problem more effectively by putting their skills together and learning how to apply their knowledge as a team to address the challenge.

7.8.5 Peer Evaluations

Team interactions can range from everyone working equally under strong leadership and team spirit to dysfunctional teams ruined by team members who do not or are unable to engage in the process. We ask each member of a team to evaluate themselves and their team, using a system based on a fictional reward. Students are given 1000 fictional dollars per team member, which they distribute between individuals (including themselves) based on the value to team. We ask each student to justify this distribution by commenting on the contribution of each team member (again including themselves). We alter the grades of students who average significantly higher or lower than 1,000. Our intentions are both to be fair and to motivate. Students know in advance that their grades may be lower than their team's grade if they do not contribute adequately. In some teams, everyone clearly valued the expertise offered by each discipline. However, in other teams, the engineers would not engage in the biological search and the biologists did not know how to engage in the quantitative assessments. More attention is needed to find ways to engage all the disciplines throughout the process.

7.9 Synthesis

This is an unusual course. We are not teaching biology or engineering, but we are asking the students to obtain a deep understanding of the specific biological system they intend to apply and translate into engineering design. A student's understanding of the biological system has to be deep enough that he or she can identify the biological knowledge that should be transferred to an engineering problem. Well-defined grading rubrics are useful so students know what constitute the traits of a BID expert. These should be directed at project evaluation, but also need to help students understand what sorts of mental process and activities help produce novel and useful (e.g., creative) designs.

Despite the unfamiliarity and challenges, students are eager to include this design process in their skill set because of the lure of invention, the novelty of BID, and its potential to lead to more sustainable practices. When given the freedom to work on a problem of their own choosing, motivation is not a significant problem. While engagement can wax and wane, depending especially on the ability of an individual to apply their domain skill set and feel useful, case studies, BIDwow, and auctioning off nature work well to maintain enthusiasm. Taking advantage of this enthusiasm by teaching bioinspired design allows us to reach quite a few learning goals, making it well worth the effort to identify some best practices. These recommendations are specifically for a course where we take inspiration from biology for design, going beyond copying or using nature.

Our experience has been that for effective BID, having biological expertise is necessary, either by having biologists on the team or available for consultation. When there is no option for student teams to include biologists, trying to find the right function from the right natural system is difficult. We recommend that experts be consulted for the best understood biological systems. Seasoned biology faculty that do research on biological systems and attend biology conferences have an edge in finding the natural systems that are rich in mechanistic details. Whereas using this expertise to give the students a good starting point may take away the chance to teach them how to search the biological literature, the students still will have many chances to hone their search strategies to find other exemplars of similar or inverted functions in extreme environments. Advanced students may even learn to find relevant examples based on phylogenetic relatedness, convergent evolution, or exaptations.

Focusing the found object exercise on some key biological functions (sensing, locomotion, and hierarchy) and comparing conjectured designs based on these solutions illustrates to the class the myriad of possibilities, teaches them about these key biological concepts and reduces design fixation. Skillful use of SBF, functional decompositions, and analogical reasoning to compare biological and engineering systems enable connections to be made between the biological functions and engineering needs. The tools for these cross-disciplinary interactions that we have developed work well. Students read the primary literature carefully and they can use SBF to focus and to keep them from getting lost in the inherent biological complexity. The newly developed SR.BID framework applied to the problem and biological solutions works well to identify the many functions to take across the divide and to evaluate analogies more deeply across functional, performance, and specification viewpoints.

When the student population is diverse, encouraging team-based problem solving is not only desirable, but necessary. Using bonus points given to the biologist who is able to explain the engineering principles or the engineer who is able to explain the biological principles tells the students that we think this ability to communicate across disciplines is useful in their training to be a practicing bioinspired designer. This cross-disciplinary practice serves as one way to keep disciplines engaged throughout the design process. Oral presentations where each team member speaks can help encourage all members to be active.

Design evaluation remains one of the more challenging aspects. Students need clear direction as to what does and what does not constitute a good problem, and to avoid common pitfalls in arriving at good designs (e.g., poor material selection, lack of appreciation of scaling, and appropriate EIA). Simple assignments pertinent to developing specific skills help students to incorporate these considerations in their final design, particularly when project grading rubrics indicate they are required.

Facilitator interaction is needed to make sure the biological mechanisms are understood correctly and the match to engineering functions makes sense, or teams may work diligently but unproductively. This is a particular problem since students consider the amount of time and energy devoted to a project as a sunk cost, which discourages them from unbiased evaluations of the potential for a given project. Timely and useful feedback is not a problem if the facilitator has a vested interest in the project. But having all these capabilities in a single instructor faced with any number of biological and engineering functions is rare, particularly when students are allowed to self-identify projects.

The final output of our course is a conceptual design that identifies the make-or-break criteria and theoretically testing the design's feasibility. Convincing tests of product success requires building and testing a prototype, which requires another semester of effort.

7.10 Conclusions and Next Steps

Problem areas that require additional attention are the search strategy for biological systems, a more complete method for teaching analogical mapping and evaluating good analogies, and evaluating good designs and good design problems. Searching and identifying useful biological systems with high potential for transfer to design still can be much improved when an expert biologist makes a suggestion or guides an exploration into the natural world. Capitalizing on evolutionary knowledge is key here, and computational methods, while promising, still cannot take the place of a skilled biologist. Although many connections can be made between biology and engineering, it is still difficult to figure out which analogical match is the best to pursue to solve the engineering challenge.

The BID class is also a research laboratory for studying BID artifacts and practices. On one hand, it has allowed us to apply, evaluate, and explore theories of creative design, analogical reasoning, and knowledge representation. On the other, in situ studies of BID already have led to the development of new descriptive theories of BID such as solution-based analogy, new knowledge representations such as SR.BID, new interactive tools such as DANE and Biologue, and new techniques such as the four box method for specifying design problems.

Our current course, focused on idea generation and conceptual design, does not include instruction in essential skills that can bring a creative idea to fruition. Translating a biological principle to a functioning device requires fundamental concept testing and experiments to build and test a BID prototype. Over and over, these new interdisciplinary designers realize that quantitative analyses can evaluate value and feasibility of the design but that implementation and testing provide the essential proof of success. Long (2012) found that making a physical prototype solves the problems of functionality, manufacturability, and improper quantitative analyses. A sequel to this course would be a fundamental concepts testing class to evaluate whether the make-or-break criterion is feasible. If it is feasible, then the

3rd class would be prototype building and testing. Some students in our classes have gone on to do this independently in other design classes. However, for certain projects, there may be some value in extremely limited prototyping within the context of our current 15 week course model. Rapid prototyping combined with hierarchical scaling have been implemented voluntarily by student groups in our BID class and this activity has gone far to evaluate designs. For certain classes of projects, incorporating this requirement would be feasible and useful.

On balance, BID provides a continuous and exciting growth process. Practicing this approach improves the facility with these new design skills, encouraging us to make friends outside our expertise. The novelty and allure of the BIDs provide motivation to go beyond the superficial and deeply understand the complexity of the problem and the complexity of the natural system.

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