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Biologically Inspired Design: A Tool for Interdisciplinary Education

Jeannette Yen and Marc J. Weissburg
Georgia Institute of Technology
Atlanta, Georgia

Michael Helms
Georgia Inst. Technology, Atlanta, GA

Ashok K. Goel
Georgia Institute of Technology
Atlanta, Georgia

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10.1 Introduction

Biologically inspired design (BID) represents a powerful and logical bridge to multidisciplinary education. Biologists and other scientists implicitly understand general principles relevant to function and design. Both biologists and engineers face the problem of identifying design criteria, yet each approaches the problem from a unique perspective. Mixing upper level undergraduates majoring in engineering with those majoring in biology, we have devised a BID class that provides both increased content knowledge in areas relevant to BID as well as practical training in methods and techniques that facilitate the identification and translation of biological principles into solutions for human challenges. The output of the course is a conceptual design that incorporates biological principles into a device or process as well as an account of how the problem was analyzed to facilitate the search for useful biological principles. Although students do not have time to realize their design, the final project report must contain a detailed quantitative analysis of the relevant governing principles that points to the feasibility of the proposed solution. We see this class as a necessary first step in providing students with the skills required to use biological principles in design, which compliments field-specific techniques in the realization of such designs.

Our concerns in devising this course are related to both developing an approach that will facilitate BID and addressing concerns about the novelty and utility of current practices in science, technology, engineering, and math education (STEM). Thus, our learning goals for the class reflect perceived problems in STEM education generally and particularly the challenges of interdisciplinary STEM programs. The most persistent and common problems facing STEM education (Baldwin, 2009) are that: (1) the large lectures and emphasis on memorizing content make students passive learners; (2) the focus on test mastery results in little retention and comprehension; (3) a lack of grounding concepts in real-world applications that establish relevance; and (4) the "cookbook" as opposed to open-ended problem solving framework.

The connection between engineering and biology presented by BID as a problem solving activity provides an excellent atmosphere in which to encourage interdisciplinarity and develop sound pedagogical practices. To that end, we have incorporated elements from the field of cognitive science to understand potential pitfalls in our teaching approaches, evaluate the way students problem solve in our BID course, and evaluate the student designs. This has given us a unique and extremely valuable perspective on our pedagogical methods.

We focus this article on our five learning goals to implement education innovation and to contribute to STEM education using BID: (1) novel techniques for creative design; (2) interdisciplinary communication skills; (3) knowledge about domains outside of their core training; (4) a uniquely interdisciplinary collaborative process; and (5) application of existing technical knowledge to a new discipline. For each of these general goals, we defined a series of specific student skills and thinking processes (learning objectives) that represent definable outcomes that we can use to assess student progress (Table 10.1). We developed the

TABLE 10.1

General Learning Goals and Specific Learning Objectives for the BID Course, and the Respective BID Course Elements Used to Encourage Progress toward Those Goals

Learning Goal	Course Objective	Course Element	Used In
Novel design techniques	Use analogical reasoning and problem decomposition to identify appropriate biological solutions	Analogical reasoning exercises, problem decomposition exercises	Design lectures, individual and team assignments to research and identify potential natural solutions, design project
Interdisciplinary communication	Describe and analyze biological and engineered system function	Problem decomposition exercises, quantitative analysis of biological and engineering systems, WWH description of biological systems	In-class quantitative assignment, found object exercises, interim and final project reports and presentations, final design portfolio
Knowledge outside core domain	Understand specific cases of biologically inspired design, including relevant biological and engineering principles	Lectures, discussion, and student research	Domain content lectures, design project
Interdisciplinary collaboration	Work effectively in an interdisciplinary team	In-class group work, team project	Analogy and found-object exercises, design project
Application of existing knowledge to a new field	Apply biological principles to an appropriate human challenge, use engineering analysis to describe biological systems	Quantitative analysis of biological and engineering systems, team project	Design project

following course components to meet the key learning goals: BID lectures, design lectures, found object exercises, quantitative assessments, analogy exercises, research assignments, interdisciplinary collaboration, mentorship, and idea journals and reflections. Below, we describe our course components in overview and link them to our general learning goals and the specific course objectives. We also provide some detailed descriptions of areas that we find either particularly troublesome or approaches that seem essential for success. Because the knowledge content of any particular course in BID is likely determined by the specific area (e.g., biologically inspired robotics) or design challenge (e.g., energy efficient structures), our focus is more on the process level. That is, we believe it is more valuable to describe how we say things, and why we do so, rather than what we cover.

10.2 Course Overview

The class is an honors-level undergraduate course, taught once a year, and is available to all third, fourth, and fifth year engineering, biology, and biomedical engineering majors. The 2009 class roster is typical of the course makeup, consisting of 15 biology students, 11 mechanical engineering students, 2 biomedical engineering students, 2 chemical engineering students, 2 industrial engineering students, and 1 student each in material science;

mathematics; aerospace engineering; nuclear engineering; environmental engineering; electrical engineering; polymer, textile, and fiber engineering; and earth and atmospheric science. Table 10.2 shows how the class has changed over the past five offerings in terms of number of students as well as lessons learned and modifications tested in next offering.

The ratio of biologists to engineers is now approximately 3:5. Initial classes were more heavily engineering oriented (with a 1:4 biologist to engineer ratio), but we found this did not work as well for at least three reasons. First, it placed too much workload demand on the single biologist on each five person project team. Second, when engineers were the overwhelming majority, the classroom environment was pragmatic, critical, and generally quiet and restrained. Changing the class mix had an easily perceptible impact, increasing inter- and intrateam communication, in-class idea generation, and participation from

TABLE 10.2

Evolution of Undergraduate BID Course, 2005–2009

1.	BID Class, Fall 2005	BID Class, Fall 2006	BID Class, Fall 2007	BID Class, Fall 2008	BID Class, Fall 2009
2. Students	12, 4 biologists	45, 10 biologists	45, 10 biologists	45, 20 biologists	40, 20 biologists
3. Assessment	Classroom observations	*In situ* cognitive study	In-class experiments, ME class experiments	Classroom observations	Analysis of final portfolios
4. Findings		Observations of design fixation and solution- versus problem-driven processes	Observations of: different representations among different groups; use of compound analogy; enhanced variation in designs	Student comments reflecting disbelief in real-world value of process, proof-of-concept experiment design requires new skills	Students express greater satisfaction with final designs; repeated practice embeds BID process
5. Changes	Initial seminar (two-credit) class, found objects, idea journals	Expanded to full three-credit course, full interdisciplinary cross listing, reduced duration of expert lectures to achieve balance between content and process education	Incorporated solution and problem-driven design process, SBF lecture, functional decomposition	Increased emphasis on ideation, changes to SBF language, analogy emphasis, restructured design project	Three design iterations to embed BID process and increase ideation; structured feasibility analysis to increase conceptual understanding and address perceived lack of real-world value

Note: An upper level undergraduate class in BID has now been offered five times at Georgia Tech (row 1). The ratio of biologists increased (see row 2: total number of students, number of biologists). Assessment techniques (row 3) too evolved during the five-year evolution of course. Row 4 specifies some of the new findings as a result of formal and informal assessments, which led to structural changes in the course (row 5) such as balancing the class between lectures and design practice, improving cross-disciplinary interactions, and evaluating the value of class-formulated bioinspired designs. SBF, structure–behavior–function; ME, mechanical engineering; BID, biologically inspired design. Sections 10.2.4 and 10.3 discuss more fully the previously published results of these assessments, but a variety of other sections also indicate how our observations have been incorporated into the course pedagogy.

nonengineering students. Finally, as a result of a local academic culture that places engineers "higher in the pecking order" than biologists and other disciplines, the additional number of biologists provides heightened emphasis on the biologists' importance to the process and generated greater receptiveness to biological concepts.

10.2.1 Course Components

Over the evolution of the BID course, we developed the following components to meet the learning objectives. We present a detailed time line in the next section, but the overall strategy of the course is to interleave domain content lectures with in-class exercises that allow students to practice their ability to describe the function of biological systems and translate these functional properties to potential human designs (analogy building, found object, and quantitative assignments). Domain lectures build from presentations of basic design theory to differences and commonalities of natural versus technological solutions to detailed content on specific areas of biologically inspired design.

10.2.1.1 Domain Content Lectures

Each year, practicing bioinspired designers are invited to discuss their current work within one class period (1/2 hours of talk, 20 minutes of discussion, 6–8 guests = 180–210 minutes total). Within this class time, these expert practioners: (a) examine the engineering principles of the biological organisms they studied; (b) demonstrate research principles for applying engineering techniques to understanding biological systems; and (c) illustrate the application of those principles to engineering design (French, 1994; Vogel, 1998), including the challenges of transferring those principles given existing technology. We have covered a variety of lecture topics over the five iterations of this course, including locomotion, biosensors, green chemistry, biomaterials, and complex systems, plus special topics from industry practitioners (Barthlott and Neihuis, 1997; Gosline et al., 1999; Geim et al., 2003; Nakrani and Tovey, 2004; Vogel, 2005; Autumn, 2006; Swanson et al., 2006; Bascompte et al., 2006; Goldman et al., 2006; Blackledge and Hayashi, 2006; Lee et al., 2007; Yen and Weissburg, 2007; Spagna et al., 2007; Muller et al., 2008). These lectures contain deep biology and engineering content specific to particular organisms, enhancing student domain knowledge, and providing examples of interdisciplinary communication and knowledge application (Project Kaleidoscope, 2004; Handelsman et al., 2004; DeHaan, 2005; Jacobsen and Wilensky, 2006).

Domain content lectures by local experts are universally appreciated by students, span a breadth of topics, and motivate the students by showing them real-world applications of the discipline. Although guest lecturers are briefed about the variety of student backgrounds and the requirement to integrate biology and engineering, experts tend to explore their topics assuming that students are prequalified in the appropriate discipline. This assumption sometimes results from unfamiliarity with the target audience but can also be the result of experts' perceptions about minimal knowledge requirements. Regardless, the end result is that either the engineers or the biologists among the students may not fully comprehend the material. In this way, each lecture presents an informal opportunity for students to bridge the gap between disciplines. It is left to individual students to direct their inquiry further, often relying on their design-team counterparts to gain a basic understanding. When encouraged, this increases the perceived value of their teammates as well as helps to emphasize that design teams collectively understand the underlying concepts covered in the lecture.

10.2.1.2 Design Lectures

Industrial design and design cognition experts teach the fundamental processes of BID (Pahl and Beitz, 1999; Ullman, 2003; Schild et al., 2004; Helms et al., 2009; Vattam et al., 2010a), brainstorming and ideation techniques (Dugosh et al., 2000), and problem decomposition and analogical reasoning (Mostow, 1989; Goel, 1997; Casakin and Goldschmidt, 1999; Nersessian, 1999, 2002; Goel and Bhatta, 2004). Typically, biologists have no design process training, and undergraduate engineers have little formal training, although they tend to have more experience. Furthermore, engineering students' experience before their senior design project tends to be with closed design problems, where answers involve the application of well-studied principles to well understood problems. In contrast, BID problems tend to be open ended and ill understood at the beginning. We devote roughly 45 to 90 minutes of class time to understanding the process of design during the initial phases of the course. This clearly is not enough for in-depth understanding, but it is sufficient to give the students minimal working knowledge of the path of the design process and how to begin.

10.2.1.3 Found Object Exercises

In order for students to gain firsthand experience with the solutions nature provides, students are asked to investigate more closely different aspects of locally available biological systems using a what–why–how (WWH) framework (an analog to the structure–behavior–function framework; Goel and Stroulia, 1996; Prabhakar and Goel, 1998; Goel et al., 2009). Found object exercises provide students with a wide range of exposure to natural objects as well as an appreciation for the sophistication of solutions developed by everyday natural objects (Vogel, 1998; Ball, 2001; Vincent, 2002). Each exercise requires students to examine objects as representative of certain functions, thus for a given biological mechanism asking the questions "*what* are the relevant components of the system?" (structure), "*why* does the system require the mechanism?" (function), and "*how* do the components interact to execute the mechanism?"(behavior). The WWH analysis of the found object exercises are paired with expert lectures, such that students are asked to identify and analyze found objects that are related to upcoming expert lectures. For example, if the lecture is on biomaterials, students are asked to find and analyze, using the WWH technique, a local biological system with interesting material properties. This deepens the students' understanding of the expert lecture topic by providing living examples of the relevant concepts. The shared WWH framework facilitates interdisciplinary communication. The hands-on interaction provides unique learning experiences (students often conduct impromptu experiments on their objects, such as putting a pinecone in a 400° oven to see how it reacts to intense heat), encourages interdisciplinary interaction using multimodal representations (Vincent and Mann, 2002; Vincent, 2002; Chiu and Shu, 2005, 2007), and increases student engagement. In this hands-on experience, both biologists and engineers (particularly the latter) are forced to rethink prior conclusions about the diversity and usefulness of natural solutions as well as expanding their previous conceptions about the way certain functions are achieved. This reanalysis can be a spring board for future designs.

10.2.1.4 Quantitative Assessments

Several lectures review quantitative analysis and provide examples to scaffold students for future quantitative homework assignments (two to three per semester), which in turn scaffold students' ability to conduct quantitative analysis for their own projects. Students use standard quantitative engineering techniques homework in their assignments to evaluate biological systems such as spider silk and gecko adhesion (Arzt et al., 2003; Blackledge and Hayashi, 2006). Engineering students gain new appreciation for the operation of biological systems and learn techniques to address the challenge of quantifying nonmonolithic, complex, dynamic biological systems. Biologists learn the precise vocabulary and mathematical rigor necessary for engineering analysis. Both groups gain increased understanding of how to evaluate constraints in the system and the importance of those constraints in applying principles as solutions. This activity prepares students for the more extensive analysis such as material analysis, performance metrics, and environmental impact assessments, required as part of their design project.

10.2.1.5 Analogy Exercises

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

10.2.1.6 Research Assignments

Students practice finding and understanding research papers written on topics pertinent to their design projects, focused either on deepening their understanding of the problem they are investigating or on enhancing their understanding of biological systems with functions that can be applied to their problem. This is the first time that most students, even senior engineering students, attempt a goal-directed search for, and understanding of, peer reviewed science literature. We introduce students to basic scientific databases and search engines and their operation. We discuss potentially valuable search strategies such as those based on model systems most likely to have solved a particular challenge (e.g., desert animals excel at water retention) and abstracting (e.g., from cooling to thermoregulation) or inverting functions (e.g., from water conservation to channeling excess water) to broaden the search space. These activities both reinforce and argue for the need to characterize appropriately and decompose/abstract the chosen problem. In addition, students have little or no experience translating from biological functions to their engineering analogs. This is a nontrivial problem because biologists and engineers often view function differently, which results in the use of different terminology for fundamentally similar processes. For instance, biologists often use context-dependent terms that relate to environment or the ecological value of a particular function rather than a more mechanistically precise term. Thus, observations or analysis of impact resistance of animal shells may be phrased in terms of "protection." This disjunction may limit the ability to find useful biological models, and although it is related to building appropriate analogies, it is a distinct and important enough problem that in our view requires discussion of useful strategies. Inevitably, students become frustrated when their searches yield either too little or too many results. Our observations suggest that students go directly to primary literature without surveying systematically the available options. Accordingly, we encourage students to consult high level general sources first and then "drill down" into the literature for more detailed analysis. This strategy seems to improve the students' understanding of the general processes and gives broader searches. It also helps identify key biological terms that may be associated with the particular function or problem under consideration. Chiu and Shu (2007) show the utility of a more formal strategy based on the same idea. We assign students the task of identifying several key papers in the beginning phase of each design iteration. The students first tell their team about their article, using the WWH format. In a team of five interdisciplinary students, each learns about 25 natural systems that could address the challenge. Then the team debates the pros and cons of their systems in an effort to narrow it down to the five best to present to the class. For the midterm, they need to tell the rest of the class (other seven teams) about their findings and justify their choice for the five best. In 2009, there were eight teams or 200 natural systems, and their usual traits were presented so other teams could pick up new ideas from this review. Outside facilitators attend and evaluate the teams to be sure they clearly present their challenge and define their problem by function. This can be one of the most exciting presentation days, as we hear about the special traits of so many natural systems and why certain ones solved or provided a partial solution or inspiration for the particular challenge.

10.2.1.7 Interdisciplinary Collaboration

Students self-assemble into interdisciplinary teams based on common interest within the first few weeks of class, although instructors may modify team composition to ensure proper engineer/biologist balance. The team formation process strives to achieve diversity in discipline, gender, and ethnicity as well as common passions. This process starts off with arbitrary teams. Each student is asked to define three issues about which they are concerned where one of them is a personal challenge. A leader is picked who aggregates the interests of their group of eight people and posts the primary challenges along with the names of the students who posed the challenge. The five leaders sort challenges into similar topics. Then all of the students examine and prioritize the challenges (blue = best idea, green = excellent idea, yellow = potential idea, red = questionable). The best ideas are selected, and the associated students are grouped with them with adjustments to balance the team by discipline, gender, and ethnicity. Instructors check to make sure each group has a diversity of engineering disciplines and at least two individuals well-versed in biology (generally biologists or biomedical engineers). These student groups form the core unit for the various class activities referred to above. For instance, we have all students in a particular group present research findings to one another or practice analogy building or found object exercises in these groups to facilitate information sharing and communication as part of our team-building objectives. Groups often are charged with presenting their findings to the general class (e.g., the three best analogies, or the most interesting found object), but students are more comfortable presenting in these small groups, and then summarizing their findings to the class. The assignments increase in complexity throughout the course and culminate in an open-ended design project for which structured class time is provided, enabling instruction and teaching intervention to occur in a timely manner. Students are asked for three iterations on their design during the semester, which tend to shift (sometimes radically change) as the project team's understanding of both their problem and biological solutions evolves. The iteration is an indispensible component, as the feedback requires students to continuously reassess their ideas and seek new analogies from natural systems. The final design requires feasibility assessment and quantitative analysis, and we find that this requirement in the later stages when designs mature leads to more satisfactory results than purely conceptual design. Students are provided an opportunity to share the early iterations and design ideas during multiple mini presentations and midterm poster sessions and final class presentations, facilitating information sharing across teams (NAS, 2005). This open-ended, project-based exercise requires students to incorporate all the lessons they have previously learned and encapsulates all the objectives established for this class.

10.2.1.8 Mentoring

Experts with appropriate specializations are assigned to mentor teams to facilitate and refine their "search image" during their project phase, and teams are required to meet with them to vet design ideas. This both tests their interdisciplinary design and communication skills and provides real-world practice. The inevitable failure from naive problem understanding and design concepts during expert interactions nearly always results in profound, positive learning experiences, deepening technical understanding and driving home the complexity of the real-world design (Barnes et al., 1997; Bilen et al., 2005; Kazerounian and Foley, 2007).

10.2.1.9 Idea Journals and Reflections

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

The text here to the end of this section is not really associated with the above topic. Please do something to sperate the text from above as per template. of our BID course are broadly consistent with the current literature on cognition of learning. Because the relevant literature in the cognitive and learning sciences is vast, we will not try to cover it here. In brief, we know that collaborative environments in which students determine and acquire their own knowledge can significantly enhance how well students master both facts and the thinking process. Specifically, (1) research on cognition of learning suggests that learning is situated in the world, especially the social–cultural world (Lave and Wenger, 1991); (2) social–cultural theories of learning emphasize collaborative construction of knowledge (Palincsar, 1998; Papert, 1991); (3) collaborative learning can enhance the quality of learning (Dillenbourg, 1999); (4) project-based learning is a useful strategy for situating collaborative learning (Blumenfeld et al., 1991); and (5) problem-based learning situates construction of knowledge (Savery and Duffy, 1995). Social–cultural theories of knowledge construction mentioned above (items 1 to 5) are receiving increasing attention in STEM education, including college-level education (Kozma, 2000), and we have paid heed to these findings in developing our approach. Our emphasis on design exercises, design projects, and research exercises positions students as active learners and fosters knowledge construction. Further, the BID course provides a "community of practice" for situating the learning of students from multiple disciplines in which students get to solve problems relevant to them.

A critical question is what kinds of knowledge should be constructed? Learning science suggests engaging students in the knowledge construction practices of professional scientists (Edelson, 1997). Our emphasis on bringing multiple BID practitioners to the BID course and assigning a professional BID scientist to each design project team exposes students to some of the knowledge construction activities of BID practitioners. This in turn raises the question of what kinds of knowledge do scientists and engineers construct. Cognitive science suggests that scientists/engineers construct models of the world (Darden, 2006; Nersessian, 1999, 2002): mental models, conceptual and explanatory models, simulative and predictive models, mathematical models, scale models, diagrammatic models, and so forth. Thus, cognitive science suggests that knowledge construction activities in science education too should emphasize construction, critiquing, and revision of models of the world (Clement, 2008). In the BID course, the design exercises, design projects, and research assignments provide opportunities for students to construct and revise models of many kinds. The design journals and reports in particular contain detailed models of the biological systems the design teams are trying to understand and the engineering systems they are trying to design. Understanding complex systems in both biology and engineering is cognitively challenging (Chi, 2005), and functional models that explain how the structure of a complex system achieves its functions are useful for understanding complex systems (Simon, 1969). The WWH (structure–behavior–function) models that we encourage BID students to explore emphasize functional explanations of complex systems. One of the outcomes from the BID course is that in the process of designing biologically inspired engineering systems, our students deepen their understanding of both biological and engineering systems. Situating model building in a practical design is a good strategy for learning about complex systems (Hmelo et al., 2000) because it entails explanation as well as prediction. This implies that the BID course, with its heavy emphasis on design presents an opportunity for students developing and deepening conceptual models of complex systems, especially biological systems.

10.2.2 Timeline/Course Flow

Our 15-week course is organized to present initial concepts regarding BID methodology and practice during weeks 1 to 4, combined with structured in-course time to apply and discuss these concepts (Figure 10.1). This organization is designed with the following purpose in mind: (1) allow students to develop the necessary interdisciplinary communication and research skills to facilitate their design project work; (2) expose students to ideation and design skills that will encourage them to work outside of their comfort zone; and (3) practice the analogical reasoning skills that facilitate the successful search for and application of relevant biological concepts.

Students assemble into groups of five to six individuals in week 2 (W2), subject to the considerations of balance and diversity discussed above. Early assignments on analogical reasoning, search strategies, and so forth, are based on the initial interests of the students. We initially ask the students to write a short paragraph of individual challenges or problems they would like to solve as way to get them to start thinking about these issues. We find that the diversity of problems, potential natural principles, levels of biological organization examined and so forth, acts to catalyze more creative thinking during the later portions of the course when students transition to their team design projects. Students define their central problem in W4, and thereafter, and most of the milestones revolve around this topic.

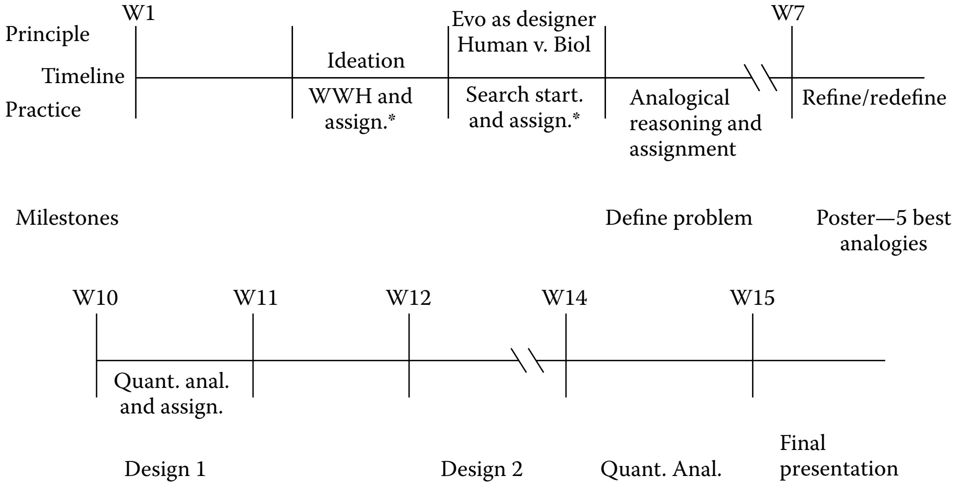


FIGURE 10.1
Weekly time line of course activities. Each division of the time line lists key components, broken up into principle, practice, and milestones. *Principle* refers to content normally presented via lecture activities, *practice* refers to activities involving mostly class or group discussions, and *milestones* represent significant assignment deadlines associated with the design project. Topical lectures on BID case studies, combined with corresponding found object exercises on the same topic occur in weeks (week number = W#) in which no activities are explicitly presented.

Our early versions (2005–2007) of the course did not specify the design challenges, but we increasingly favor using a broadly defined topic (e.g., water conservation [2008], energy efficient buildings [2009]) within which student teams determine specific challenges. Although this potentially limits students' creative expression, we believe this is balanced by the fact that it provides focus, encourages students to tackle problems that are appropriately challenging, and fosters greater exchange among groups as a result of this common focus. It also allows us to analyze and present the entire range of initial processes considered by the students as potential problem topics—this frequently elicits discussions from the students on connections between specific areas or areas that may be ignored. The end result is that students begin to understand the advantages of multifunctional solutions, or specific areas that are under consideration and that may be particularly amenable to applying biological principles.

Because BID often involves identifying relevant principles that may not be immediately obvious, we encourage students to take a broadly comparative approach early on and seek breadth rather than depth at this stage. A common problem in engineering education is that students feel pressure to come up with solutions quickly and are uncomfortable with ambiguity or uncertainty. In the BID process, we intentionally destabilize their thought process, asking them not to settle on their first solution and instead engage in a comparative approach. Kazerounian and Foley (2007) state that ambiguity enhances creative thought, and we agree with their findings. Thus, the first project milestone beyond defining their specific challenge is to mine the biological literature for what they consider the five best potential systems (analogies) for their challenge. The previous assignments in literature searching (W3), analogical reasoning and problem decomposition (W2 and W4), and the ongoing found object exercises are all designed to prepare them for this task. Students present their initial problem decomposition and analogies in a poster session in W7, where they receive feedback from instructors, expert facilitators, and other students. If necessary, they use this feedback to refine and redefine their problem. These redefinitions usually occur as a result of inappropriate analogies that indicate a poorly phrased problem or bad match to the biological system. Interestingly, the problem redefinition can occur in one or two ways: students may refine their problem statement because their choice of analogies reveals they need a more accurate description to find appropriate biological solutions, or they revise their problem statement to correspond to principles actually revealed by the biological systems they have chosen. This corresponds roughly to problem-based versus solution-based reasoning, and reveals both the iterative and bidirectional cognitive process (Helms et al., 2008) involved in BID (see below).

Preliminary project designs are presented in W10 and W12 as mini presentations. This involves detailed problem decomposition and how the proposed solution maps on to this problem (see Section 10.2.4.1). The design in W12 is not simply a refinement of that in W10—it requires that students apply a new concept from a different biological principle. This encourages students not to be fixated on particular design ideas before they have a chance to explore multiple potential solutions. The quantitative analysis milestone assures that students have used quantitative reasoning to assess the potential feasibility of their solutions in light of the problem constraints and is focused on examining whether their solution can perform the appropriate function it is designed to achieve. We specifically direct the students that this should not be a market analysis or a cost–benefit calculation. Although we realize these are design skills as well, they are tangential to our concerns, which relate to the ability of students to map potential biological principles to achieve functionality necessary to solve a human centered challenge. Each team does a final presentation where extra points are given if a biologist presents the engineering principles or the engineer presents biological principles. Project mentors and outside experts are invited to this final critique to provide feedback for students to use for preparing their final portfolio.

10.2.2.1 Portfolio Design

A brochure is published for each team, consisting of eight glossy pages to present the design process and outcome as follows: (p1) title to provide a branding and a list of team members (major + photo) to recognize their intellectual property; (p2) a definition of the problem and its significance; (p3) an assessment of existing solutions; (p4 and p5) presentation and decomposition of biological analogs; (p6) a description and representation of the design; (p7) quantitative analyses of function, materials, and environmental impact; and (p8) bibliography and acknowledgments. This portfolio is prepared as a pitch to a venture capitalist to convince them to invest in the research and development for the design. Students have brought these to job interviews and report that the portfolio triggers lively conversations about BID.

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

10.2.3 Evolution versus Design

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

10.2.3.1 Evolution as a Design Process: Challenges and Opportunities

One of the great strengths of interdisciplinary teaching using the BID framework is that both biologists and engineers understand design and function, in the context of biological and engineered devices and processes, respectively. This provides a natural common language to facilitate communication. However, the actual use of biological principles as potential engineering insights depends on more than a common framework; it requires a basic understanding of the process of evolutionary "design" and, in particular, how this process is different from that of human, conscious, intentional design. We consider this an essential lesson for both engineers and biologists. Other authors have drawn attention to this distinction (Vogel, 1998; Full, 2001) but do not discuss the implications for effective BID teaching.

The major aim of our discussion of evolution as a "design process" is to make plain the differences between intentional design to produce a desired function and the unintentional, trial-and-error design process of evolution. The comparison of evolutionary and human design places concepts immediately familiar to biologists and engineers in a common framework and immediately facilitates communication across disciplines. Additionally, understanding the major differences between human and evolutionary design enables students to interrogate the biological world more effectively as they search for design ideas.

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

The core lesson here with respect to BID practice is that the search for biological principles requires an appropriate assessment of the strengths and weaknesses of evolutionary design. Biological principles have resulted in innovative designs (for a summary, see Vincent et al., 2006) but will not be useful unless there is an analogous problem that requires evolutionary adaptation. On the basis of the above analysis, students must recognize a number of important pitfalls or caveats for the strategies they use to mine the biological literature for potential solutions. These caveats directly address misconceptions students (even biologists) sometimes have about evolution and lead to a better framing for how to acquire knowledge useful for solving a particular problem. First, because a given solution may evolve via a number of mechanisms, one must have a firm understanding of the appropriate level at which to interrogate a biological system. Too narrow a focus may be misleading by identifying specific ways a problem may be solved rather than the unifying principle. Second, finding the optimal solution from biology may not always be possible, as opposed to revealing a general principle that can be implemented in a particular way that is best for a given technological problem. Third, identifying robust principles may be difficult given the nature of historical constraint. Searching biology for solutions must include comparisons across related groups that are less likely to share solutions because of history. Convergent evolution, where organisms from completely different lineages arrive at the same solution to similar conditions (flight by the insect, bat, and bird for instance), tells us what are the key mechanisms. It may be most useful to start with these solutions when translating them into engineered designs. In contrast, comparing across groups of animals that are related (e.g., species within a genus) may reveal how solutions are fine tuned for very specific challenges—that is, parameter values for system properties that are maximally beneficial for a given specific set of constraints. Finally, biology may or may not be an appropriate guide given the difference between the (typically) unifunctional engineered and multifunctional biological approaches. However, biology may reveal ways to implement multifunctional solutions, if such a thing is required, desired, or necessary in a design. Aside from the practical importance of these considerations for BID, they also develop skills in a number of areas that seem critical for problem solving generally, such as appropriate identification of the general issues, recognition of constraints, and the utility of comparative analysis to reveal general principles.

We find that establishing the salience of biology to engineering is strengthened by showing similarity of constraints as well as problems. Clearly, the analysis of function as both an engineering and a biological pursuit helps define a common problem framework, but the discussion of problems associated with evolution as a "designer" may lead to students questioning whether BID is a successful way of thinking. Thus, we conclude with a short discussion of "evolutionary" constraints in a common device—the QWERTY keyboard. As chronicled in a number of different analyses (Noyes, 1998), the present incarnation of QWERTY is the result of many of the same phenomenon we discuss in the context of biological evolution, including historical constraint, competing design requirements, and incremental change. Feeding back from engineering into biology helps solidify the concepts and strengthens the link between the engineering and biological domains.

10.2.3.2 Setting the Stage: Technological versus Natural "Solutions"

We have developed a "lecture without words" that makes students aware of the differences between natural and technological approaches to problems as a prelude for their immersion into specific BID projects. Our purpose is threefold. First, we wish to make students aware of how differently biological processes "solve" particular problems as a way to enlarge the design space. Students may be unaware of the confines of technological approaches without some exposure to natural principles and how these may differ from the more familiar solutions. Second, we wish to identify some of the general principles used by biological processes and reinforce the necessity to understand those processes before engaging in BID. This emphasizes the inherent multidisciplinary nature of BID as a process that requires depth in biology and engineering that can only be gained by dialog between practitioners of both these fields. Finally, we use this exercise to drive home some of the potential problems in transferring principles from the biological to the technological domain. Appropriate mapping of biologically based solutions onto technological challenges requires understanding constraints, which may be so dissimilar as to prevent application. By example, many properties of biological materials depend (at least partially) on hierarchy, but constructing hierarchically organized materials seems technologically challenging as it often may require control of materials at nano- and microscales, which is pushing the limits of many of our manufacturing processes. Similarly, task allocation and distributed decision making in groups of organisms often takes place in a context where organisms are closely related, which results in a situation in which the evolutionary fitness of the group is closely tied to the evolutionary fitness of individuals within the group. Applications of some of these principles may well depend on analogous situations in the organization of collective human systems.

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

10.2.4 Analogy Exercises

In practice, BID is a technique for complex problem solving using analogical design, where novel designs in one domain (engineering, architecture, etc.) are created by drawing upon solutions and patterns in the different domain of, for example, biology (Benyus, 1997; Bar-Cohen, 2005). Recent research on design, especially creative design, has explored the use of analogies in proposing solutions to design problems in the conceptual phase of the design process (e.g., Zhao and Maher, 1988; Mostow, 1989; Gross and Do, 1995; Qian and Gero, 1996; Goel, 1997; Casakin and Goldschmidt, 1999; Goel and Bhatta, 2004; Davies et al., 2009). For example, Qian and Gero (1996) and Goel and Bhatta (2004) present computational models for generation of new design concepts by cross-domain analogies guided by structure–behavior–function models. Casakin and Goldschmidt (1999), Gross and Do (1995), and Davies et al. (2009) describe the generation of design concepts by visual analogy. Recognition of BID as a process of analogical transfer also has led to computational tools for supporting BID (Chakrabarti et al., 2005; Chiu and Shu, 2007; Vattam et al., 2010b). Idea-inspired application represents the functions, behaviors, and structures of biological and engineering systems in a uniform representational scheme called SAPPhIRE. BID however remains cognitively challenging despite the advancement of relevant theories and supporting tools.

Our first iterations of the BID course implicitly incorporated many ideas and techniques of analogical reasoning. We know from Dunbar (1995) that in general the analogy making behavior of humans in naturalistic and laboratory settings is quite different: people make more, and more interesting, analogies in their natural environments. Thus, over the last few years, we have made several empirical findings about analogical reasoning in BID (e.g., Helms et al., 2008, 2009; Vattam et al., 2010a,b). We then analyzed these findings from the perspectives of design theory and design cognition and identified several patterns of content and process of analogies in BID, for example, problem-driven and solution-based processes of BID (Helms et al., 2008, 2009; Vattam et al., 2010a,b) and compound analogy (Helms et al., 2009; Vattam et al., 2010a,b). Over time, we explicitly included these content and process accounts into our teaching. Below we describe several patterns of analogical design reasoning we have identified and which we now use in our teaching.

10.2.4.1 Problem Decomposition

Once students attain a deeper understanding of the biological principles from reading the primary literature, they are ready for the process of translation. This requires both problem decomposition and analogical reasoning. For problem decomposition, the designer iteratively decomposes the presented problem into subproblems to create a problem hierarchy. Assuming that the problem is decomposed along functional lines (other decompositions are possible), each node in this hierarchy is a function to be achieved. A representative decomposition (see Chandrasakaran, 1990; Figure 10.2) illustrates one potential functional analysis of the process of how animals walk on sand. This particular decomposition was derived collectively by the class as an instructor led in-class exercise. The class was given relevant primary literature (Li et al., 2009) before this discussion.

Two key functions of movement over sand are balance and propulsion, forming the first level of the hierarchy of the decomposition. To achieve the function of balancing, the organism can minimize tilt or recover level (top left side). Tilt minimization is then achieved by either not sinking or by maintaining level. These functions may require the organism to distribute their load over a large surface or avoid obstacles. Approaching the decomposition from the specific kinematics (lower right side), we define how a sand walker gains purchase in the sand through controlled shearing, surface area contact, adhesion,

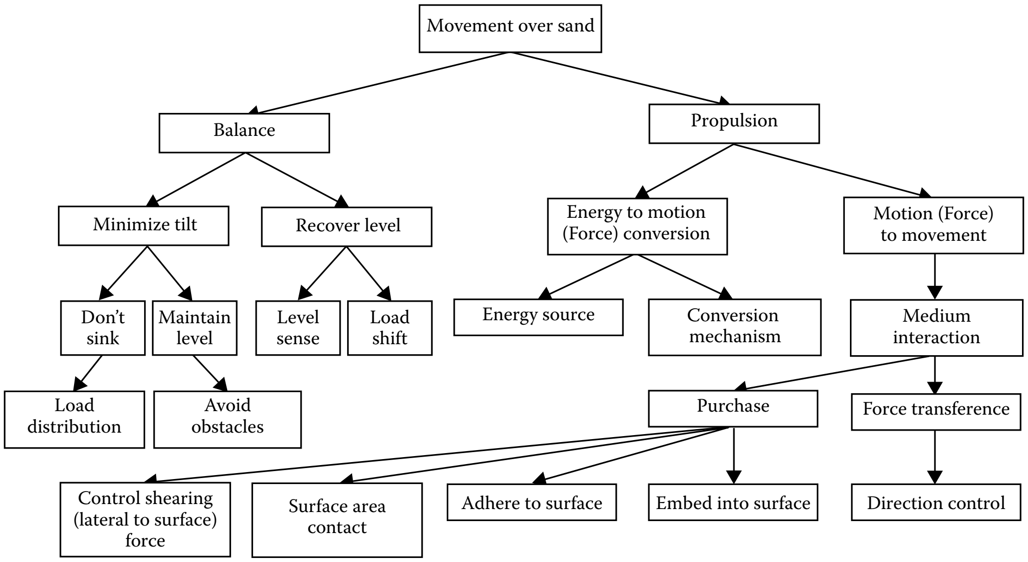


FIGURE 10.2
Functional decomposition for movement over sand.

and embedding into the surface. This is abstracted to the general function of interaction with the medium that provides force for movement, thus propelling the organism. Note, however, that for these problem decompositions, there are no right or wrong decompositions, only more or less useful ones. To be more useful, it is important to identify functions, clearly articulating why the organism performs these functions. Deep thinking about the behavior requires understanding how the function works and the mechanisms and processes involved. Here, awareness of common principles helps to abstract to higher-level more general functions that may be applied more universally, thus expanding the usefulness. Although it is necessary to play with the arrangement to make the best links from structures to mechanisms to functions, one also must make commitments and move on.

When developing these problem decompositions, each function can be used as a cue to retrieve known solutions that achieve that function, thus expanding the number of alternative solutions. Solutions are transferred to the current problem and aggregated to generate the overall solution. We show how an analysis of plant growth provided inspiration for improving solar energy conversion (Figure 10.3).

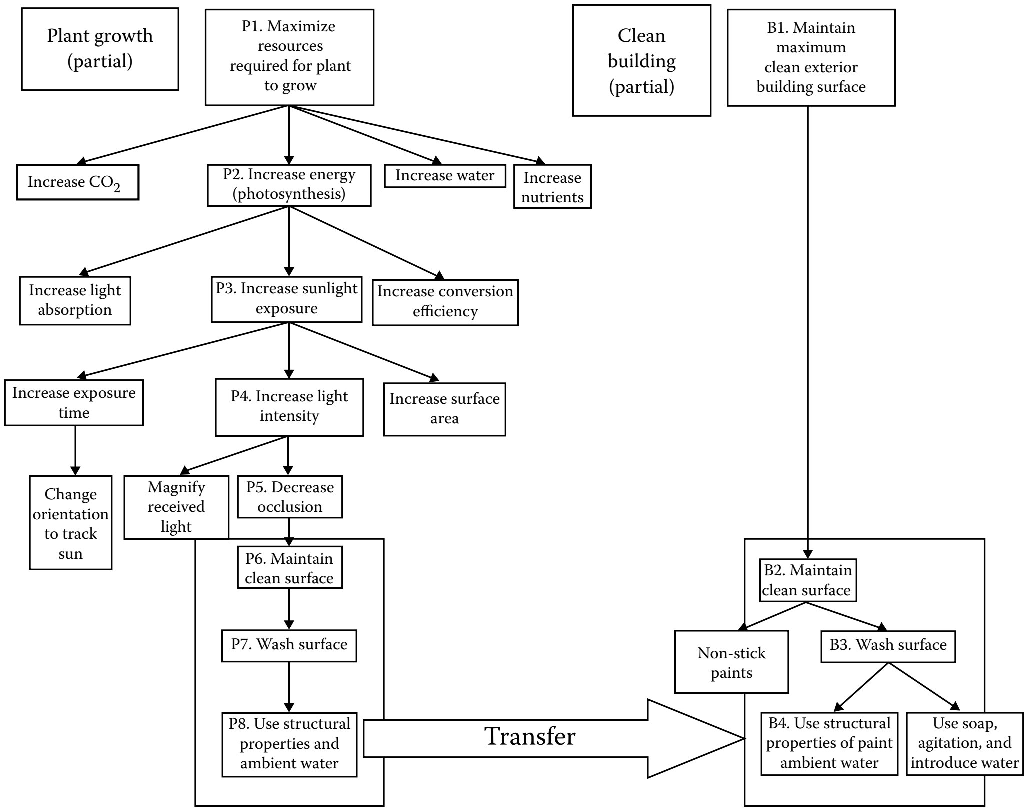


FIGURE 10.3
The functional decomposition of the process of plant growth was constructed in parallel to similar analyses of the problem of solar energy conversion. By specifying the structures and processes involved in the mechanism of photosynthesis by the plant and the mechanism of photon conversion in solar collectors, a common solution—use of structural properties and ambient water to keep surfaces free of debris that could occlude light capture—led to a bioinspired solution of self cleaning photovoltaic surfaces. (Adapted from Vattam, S., M. Helms and A. Goel, "Biologically-inspired innovation in engineering design: a cognitive study," Technical report, Graphics, Visualization and Usability Center, Georgia Institute of Technology, GIT-GVU-07-07, (2007).)

Here both the natural solution and the problem have been decomposed into functions until a level is reached where functions overlap and a crossover can occur. In this example, the interaction of surface structural properties and ambient water was the inspiration for a self-cleaning mechanism.

10.2.4.2 Compound Analogies in BID

Our analyses of the design products and processes in BID revealed a complex interplay between solution knowledge, analogical references, and problem understanding, leading to the incremental, iterative development of compound analogical solutions. In short, the process of compound analogy involves the use of two or more analogies in the design of a target system (Helms et al., 2009; Vattam et al., 2010a). Beginning with an initial problem description P1, one is reminded of an initial source S1 (Figures 10.4 and 10.5). During the process of transferring information from the source to the target problem, a greater understanding of the target problem evolves. The new understanding P2 may include new subproblems, constraints, or functions to be accomplished, which may in turn remind one of an additional source S2. This additional source then may be applied to the new problem to yield a yet more elaborate problem description P3. This problem description and its resulting solution are said to be a compound analogy as it is a result of the application of more than a single analogical transfer. Figure 10.4 illustrates how a problem, decomposed into its functions, can be mapped onto or matched to a series of analogues.

We draw two main conclusions from our analysis. First, successful BID requires that designers carry representations of previous problems that are organized at different levels of abstraction and aggregation. This organization facilitates the decomposition of solutions and allows solution analogs to be retrieved with cues taken from each level. Second, the mapping between the problem space and a target solution allows for identification of potential new solutions but also permits inferences about problem decomposition. The design problem therefore evolves as a result of the interplay between the problem decomposition and the analogy-making process. The use of compound analogies illustrates that value of incorporating principles that are deeply understood, instead of mimicking a given system. It results in creative solutions that incorporate diverse principles that may not be found in a single natural example (e.g., "geckel" combines adhesion of geckos and mussels; Lee et al., 2007). It also facilitates reevaluation and reinterpretation of the design problem and refinement of potential solutions.

This process explains complications that often arise during reintegration when the solutions from disconnected analogies do not integrate cleanly at their boundaries or have overall constraint mismatches. Each new node from the source solution decomposition integrated into the problem space can act as an additional cue for retrieving another set of solution analogs. This process can continue iteratively leading to the incremental development of the problem space. The designer can evaluate the partial solutions available at every stage of the design process and decide to take further actions. The iterative feedback between these two processes accounts for the incremental evolution of design problems.

10.2.4.3 Multifunctional Design and Problem-Driven versus Solution-Based BID

Multiple problems (Figure 10.5, P1–P5) often can be addressed by a particular natural solution due to the multifunctionality of natural systems. An example of a problem having

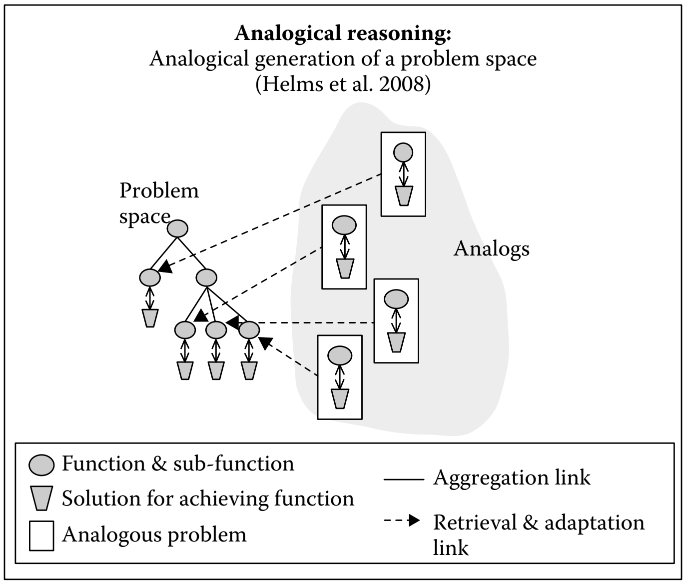


FIGURE 10.4
Analogical reasoning matches functions of the problem to those found in the natural systems.

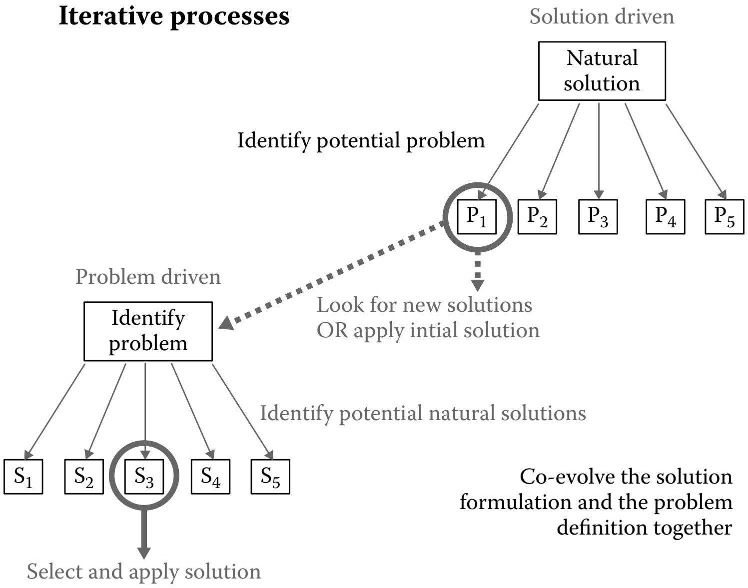
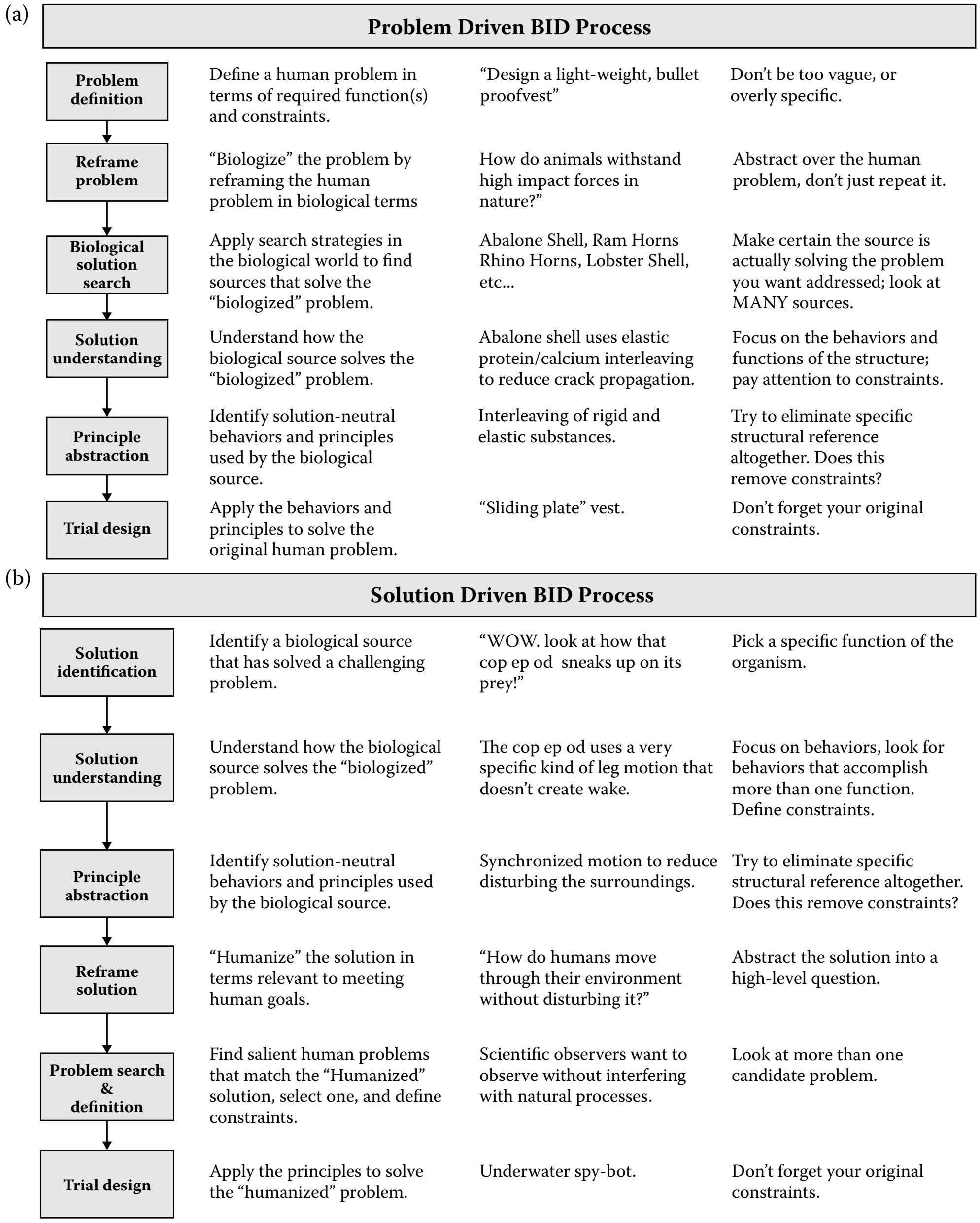


FIGURE 10.5
(See color insert.) A single natural solution (on the right) may solve one or more problems; one problem (on the left) can in turn be solved by one or more natural solutions.

more than one primary function is how the bulletproof vest provides both impact and puncture resistance. Hence, a single analogous natural system, such as an abalone shell, potentially may be applied to more than one problem and represents a multifunctional solution. Interestingly, we have noticed that multifunctional solutions are more likely to arise when students use a solution-driven versus problem-driven approach.

As alluded to above, the BID can be motivated by a technological problem or potentially useful biological properties (problem- vs. solution-driven approaches; Helms et al., 2008; Figure 10.6). Both approaches have resulted in the successful application of biological concepts to technological challenges (Yen and Weissburg, 2007). The usual problem-driven design process (Figure 10.6a) begins with a technological challenge, such as



(a) **Problem Driven BID Process**

Problem definition	Define a human problem in terms of required function(s) and constraints.	"Design a light-weight, bullet proofvest"	Don't be too vague, or overly specific.
Reframe problem	"Biologize" the problem by reframing the human problem in biological terms	How do animals withstand high impact forces in nature?"	Abstract over the human problem, don't just repeat it.
Biological solution search	Apply search strategies in the biological world to find sources that solve the "biologized" problem.	Abalone Shell, Ram Horns Rhino Horns, Lobster Shell, etc...	Make certain the source is actually solving the problem you want addressed; look at MANY sources.
Solution understanding	Understand how the biological source solves the "biologized" problem.	Abalone shell uses elastic protein/calcium interleaving to reduce crack propagation.	Focus on the behaviors and functions of the structure; pay attention to constraints.
Principle abstraction	Identify solution-neutral behaviors and principles used by the biological source.	Interleaving of rigid and elastic substances.	Try to eliminate specific structural reference altogether. Does this remove constraints?
Trial design	Apply the behaviors and principles to solve the original human problem.	"Sliding plate" vest.	Don't forget your original constraints.

(b) **Solution Driven BID Process**

Solution identification	Identify a biological source that has solved a challenging problem.	"WOW. look at how that copepod sneaks up on its prey!"	Pick a specific function of the organism.
Solution understanding	Understand how the biological source solves the "biologized" problem.	The copepod uses a very specific kind of leg motion that doesn't create wake.	Focus on behaviors, look for behaviors that accomplish more than one function. Define constraints.
Principle abstraction	Identify solution-neutral behaviors and principles used by the biological source.	Synchronized motion to reduce disturbing the surroundings.	Try to eliminate specific structural reference altogether. Does this remove constraints?
Reframe solution	"Humanize" the solution in terms relevant to meeting human goals.	"How do humans move through their environment without disturbing it?"	Abstract the solution into a high-level question.
Problem search & definition	Find salient human problems that match the "Humanized" solution, select one, and define constraints.	Scientific observers want to observe without interfering with natural processes.	Look at more than one candidate problem.
Trial design	Apply the principles to solve the "humanized" problem.	Underwater spy-bot.	Don't forget your original constraints.

FIGURE 10.6
(a) Problem-driven bioinspired design process. Reframing the problem in terms of natural processes is a key step in bioinspired design. Principle abstraction allows the natural solutions to find a broader range of application to technological challenges. (b) Solution-driven bioinspired design process. Often, the particular way that an organism solves a problem is so unique and fascinating that it drives the process to reverse engineer nature, searching for a human challenge that could be solved by the natural process. Again principle abstraction is an essential step in enabling a successful translation of natural functions to technological mechanisms.

designing a lightweight bulletproof vest, which we put before students as an exercise. We used functional indexing and reframed the problem in biological terms by asking, "How do animals withstand high impact forces in nature?" Subsequent biological literature searches revealed how different organisms withstood impact using structures with unusual construction that dissipate impact forces (ram's horn, abalone shells, and lobster carapace). The search also identified articles explaining these phenomena from a materials standpoint, with one potential mechanism consisting of the interleaving of rigid calcium carbonate tiles and elastic protein layers (Lin and Meyers, 2005). The general principle of offset rigid structures with flexibility imparted by more elastic layers inspired a design for a "sliding plate" vest. In contrast, the solution-driven process searches for a problem that can be solved by a selected natural system. In this example (Figure 10.6b), a series of articles described how an aquatic microcrustacean was able to approach a prey stealthily, using a specific kind of leg motion (van Duren and Videler, 2003) that creates a laminar wake with minimal water disturbance (Yen and Strickler, 1996). Synchrony in the propulsion mechanism provided a general mechanism for stealth in water. Reframing the solution in terms relevant to meeting human challenges, the problem was defined by asking this question, "How can humans move through their environment without disturbing it?" This led to the implementation of a novel mechanism for an underwater spy-bot that could be used to observe without interfering with natural processes.

Clearly, biological knowledge provided inspiration for novel designs through both the problem-driven as well as the solution-driven processes. Still, we see evidence that solution-driven and problem-driven approaches are different with respect to the final design outcome. An analysis of nine BID design projects in Fall 2006 showed (1) solution fixation limited the solution-driven design process, (2) multifunctionality dominated the solution-driven process, and (3) solution-driven approaches had a strong structural focus possibly the result of limited incubation time or limited understanding of the mechanisms responsible for the function.

These results make plain the different advantages of each approach, and possibly reveal something about the underlying design process. Whereas solution-centered approaches produce fixation probably because of the strong initial focus on a particular organism, the problem-driven approach tends to restrict the ability of the designer to reach outside of their initial framework and engage multifunctionality. Thus, we believe it is critically important to encourage students to iterate the process and switch between problem and solution focused approaches. Just as the iteration between technological problem and biological analogies may drive innovative compound solutions, it also may drive expansion and redefinition of the problem to incorporate multifunctionality and, in complementary fashion, reduce the tendency toward design fixation.

10.3 Studying the BID Process—Lessons Learned

Our course represents the efforts of not only biologists and engineers but also contributions from cognitive scientists engaged in understanding human cognition and creativity. Our course strategy has been deeply influenced by findings in that field. In addition to education as a design microcosm, the classroom also serves as a research platform for understanding the process of BID specifically and analogical reasoning generally. We have studied the activity of classroom participants for the last three years, examining the processes they use, and intermediate and final design representations. Analysis of this has yielded a number of cognitive theories of BID. Although such theories may or may not generalize beyond classroom design, it is our hope that this information will enhance existing BID education practices specifically and interdisciplinary education generally as well as provide useful insight for professionals in the design field.

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

10.3.1 Novel Techniques for Creativity

One of the driving goals for BID is the increased attribution of creativity to BIDs. We know that analogy use and design fixation present significant challenges to students in BID. With respect to analogy use, for a single design project, we found that students investigate between 2 and 30 different cross-domain analogies, and roughly half of the projects include more than one cross-domain analogy in their final design solution (Vattam et al., 2007). The way these analogies are used in practice led the cognitive scientists to the development of a theory of compound analogical design (as presented in Section 10.2.4.2). With respect to design fixation, despite the requirement to investigate many design alternatives, as many as 66% of design projects use variations on initial design for their final design project, and only between one and three design variations are ever explored during the process (Helms et al., 2009). In response to this study of the 2007 iteration of the class, we added the requirements that students find 25 potential biological examples and work up two preliminary designs that use different principles.

10.3.2 Interdisciplinary Communication Skills

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

(i) "I have also learned to communicate with those in other fields more effectively and hopefully to communicate with those in my own field more effectively."
(ii) "Working with two biologists in my group over the course of the semester though, I think I did learn how to better understand biological systems and speak in biological terms."
(iii) "… the most useful skill I learned this semester was learning to talk to engineers. For example, I had never heard of a stress-strain curve before, but I am happy to draw one for you now."

Additionally, with respect to representation use, for a given biological system, we know that engineers prefer graphs/tables (90%), whereas biologists show equally divided preference among text, graphs/tables, and structured knowledge representations (Helms et al., 2010). This suggests that part of the communication gap lies not in vocabulary, but in representation preferences. We also note (in Helms et al., 2008) that students communicate at varied levels of abstraction, from basic shapes to drawings to structure to functional abstractions.

10.3.3 Knowledge about Domains outside of Core Training

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

(i) "Interactions and cooperation with the logical, calculating minds of engineering students have allowed me to learn how to look at a problem from a logical point of view rather than the creative, 'big picture' perspective I often approach a challenge with."
(ii) "I know some biology majors, but interacting with them in this class really surprised me about how differently people in different majors think…. It is surprising how specialized your thinking becomes after just two or three years without you realizing it."

10.3.4 The Interdisciplinary Design Process

A key finding from our *in situ* cognitive study (Vattam et al., 2007) is that despite problem-driven instruction, approximately half of our students follow a solution-driven approach and fixate on an interesting biological mechanism and then look for problems for which that mechanism is a good solution. This finding repeats itself consistently year after year. Furthermore, as a result of (1) the hunt for analogies appropriate to the designers' problems and (2) the need to understand the often complicated foreign (to engineers) underlying mechanisms of analogous biological systems, a great deal of design time is spent searching for and understanding biological systems. This search for understanding has a tendency to reduce the time available for problem research and design conceptualization. One of the key challenges reported in (Nelson, 2009) is the notion of sunk cost (Arkes and Blumer, 1985; Olds et al., 2005). The implication is that time is a highly valued resource, and that after an investment in understanding an initial solution/design, students perceive too high a switching cost (in terms of time) to investigate alternative solutions. The account in Nelson et al. (2009), which focuses on some of our design teams, also provides valuable information on the evolution of student understanding of the design process, for example, student confusion between problem space and application space (Ahmed et al., 2003; Atman et al., 2007). Student reflections also demonstrate a heightened appreciation for the complexities of the design process:

(i) "I thought that the class was a good departure from the more traditional engineering courses, where formulas and methods are taught from a textbook and tested. Although it is necessary that engineers are able to understand the basic disciplines… the ability to think creatively about real-world situations seems to be a more important skill."
(ii) "Personally, I felt incredibly good about the outcome. I had never designed something of that caliber from start to finish; doing so was wonderful."

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

10.3.5 Application of Knowledge across Domains

We struggle as educators to provide students with knowledge contextualized in a way that enables use of that knowledge outside of a classroom setting (Downey and Lucena, 2003; Bras, 2003; Norton, 2005). The exponential increase in patents based on biological principles (Bonser and Vincent, 2007), and the numerous examples of successful BID products (Allen and Smits, 2001; Chan et al., 2005; Ayers and Witting, 2007; Capadona et al., 2008; Yeom and Oh, 2009) point to the value of BID as a practice worth teaching in its own right. Yet, we teach BID not only for its practical value. All of the above-listed skills are important, whether performed in the context of BID, in understanding biological systems, or in any interdisciplinary project. Additionally, as the following quotes exemplify, BID provides a new context for the application of knowledge students already have.

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

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

10.4 Future Directions

BID is an active and exciting field that captures the imagination of people from many fields. Learning how this process works and using this approach trains us to think "outside the box" and find links between different disciplines. Perhaps for this reason as well as the success of BID in developing new products or processes (Vincent et al., 2006; Bonser and Vincent, 2007), there has been increasing interest in teaching BID. For instance, although accounts of pedagogy are not common, courses incorporating BID occur at the University of California, Berkeley (robotics), Duke University (materials), and University of Maryland (robotics) as well as centers at the University of Bath, Harvard University (The Wyss Institute for Biologically Inspired Engineering), and University of Applied Sciences at Bremen. This is only a partial listing, and undoubtedly BID occurs in other programs as well.

A central issue is that we currently lack strong cognitive science accounts of the thinking processes that underlie BID, and the necessary elements for successful teaching are not currently clear. Still, there is some consensus that BID requires the ability to describe function of human and biological systems and the effective use of analogy. Vincent et al. (2006) have pioneered the use of TRIZ as a system to accomplish these goals. TRIZ is a method to describe principles that underlie function and define analogies between systems on the basis of shared properties. It can be very useful in identifying potential biological principles for a given problem, but it is not a cognitive science account of the underlying thinking process. Some current research is providing such accounts of analogical reasoning in BID, which may provide a basis for understanding and perhaps enhancing creativity (e.g., Vattam et al., 2010c).

It is also appreciated that a limiting factor in BID is domain-specific terminology that diminishes the ability of biologists and engineers to indentify equivalent systems or principles across their respective fields (e.g., Chiu and Shu, 2005). Bruck et al. (2007) indicate this as a factor that constrains how well engineers can identify principles useful for building biomimetic robots. Computational tools are being developed that help nonbiologists to retrieve information from the biological literature (Chakrabarti et al., 2005; Bruck et al., 2007; Chiu and Shu, 2007; Sarkar and Chakrabarti, 2008; Vattam et al., 2010b). These often take the form of databases or repositories that allow students to find relevant examples or systems for natural-language searching of the literature that help reduce the burden of field-specific terminology.

Another area of difficulty is that true transference of biological principles requires the fabrication of a device or the development of a process based on the biological principle. Our course stops short of this goal as a result of our decision to focus students' attention on using BID during the initial concept generation and surveying different areas of BID. Students clearly do not have the benefit of translating their principles into a realized device where they may understand more fully the relevant principles and gain valuable experience in understanding the steps required to engineer complex systems (Bruck et al., 2007). Covering a more limited topical area (e.g., robotics, materials) and providing students knowledge required to fabricate their devices can result in students developing many of the same skills as we sought to encourage in our own course (Bruck et al., 2007). Whether to pursue a more limited subject area and proceed all the way to fabrication (i.e., a vertical approach) versus a more comparative course stressing the role of BID in ideation (i.e., our horizontal approach) may depend on the student population, and the extent to which grounding in particular technical approaches is desired. Technical expertise is more likely to result from a more focused, vertical organization around a given subject area.

In terms of design theory, there is a need for a theoretical approach for what *content* from the biological world is applicable for design. A formal design process and theory that leverages cognitive science, learning theory, engineering education, and design theory can improve how we teach and how well we can learn to use this process. Metrics for evaluating the output, in terms of creativity, communication, cross-domain transfer, and design skills are needed. BID can be used to bring science out of academia and increase the respect people have for nature as a mentor and source of knowledge for practical devices, materials and processes.

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