AC 2008-2239: BIOLOGICALLY-INSPIRED DESIGN: A UNIQUE MULTIDISCIPLINARY DESIGN MODEL

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Biologically-Inspired Design: A Unique Multidisciplinary Design Model

Abstract

Many natural organisms have developed and adapted solutions to technical challenges that are similar to those encountered in the engineering world, including developing hard and tough materials, optimizing the division of labor and resources, maintaining constant temperature, and generating efficient propulsion in air and water. Biologically-inspired design (BID) refers to applying such natural solutions to generate innovative design solutions for human-encountered technical challenges. Such design is inherently multidisciplinary, bringing together disciplines both from engineering and the sciences. This article reports on ethnographic studies of multidisciplinary student design teams and a multidisciplinary team of educators in a senior-level undergraduate BID class offered at our institution. The most significant challenges came at the administrative level of the course among the multidisciplinary educators rather than among the multidisciplinary students. Differing perceptions about design and failure to collaborate as a multidisciplinary team among the educators led to unanticipated challenges during the administration of the course. The potential for discipline-specific views about design is identified as is the need for multidisciplinary educators to work together as a team both in defining the goals of a course as well as in advising students in the course.

Introduction

Current and future technical challenges are expected to become increasingly complex, requiring contributions from multiple disciplines. For this reason, ABET accreditation criteria and the Engineer of 2020 report have identified the ability to function on multidisciplinary teams as an essential skill for current engineering students to develop. Many engineering programs try to achieve multidisciplinary student experiences through design classes that bring together students from different fields within a discipline, or occasionally different departments within engineering[1,2]. A broader level of multidisciplinarity can be achieved in Biologically-Inspired Design (BID), which refers to the use of natural organisms and systems as inspiration for designing solutions to engineering challenges[3-6]. Such design inherently requires truly multidisciplinary collaboration, incorporating knowledge both from the biological domain in order to identify natural sources of inspirations as well as from the engineering and design domains in order to physically realize the inspirations. Furthermore, while in typical engineering design the problems are posed at the outset, the reverse is often true in BID. Interesting natural solutions are often identified first, applications are sought for those solutions second, and the natural solutions are adapted and applied to the applications last[7]. Such a design process more closely resembles entrepreneurship than design and offers a unique opportunity to observe practitioners' abilities to identify applications, evaluate existing technologies, and define problems, all while working on multidisciplinary teams.

This paper reports on an ethnographic study of an undergraduate design course explicitly focused on bringing together students in a truly multidisciplinary setting, spanning across colleges. Ethnographic studies are anthropological tools used especially within the social sciences for understanding the world view of a group of subjects. Recent efforts within engineering education have focused on drawing in qualitative research methodologies from the social sciences, including ethnographic observation[8,9]. Past ethnographic studies on engineering design education focused on understanding student motivation and adoption of taught design principles[10]. One study into design education developed verbal protocols for studying the design process undertaken by students, with the goal of correlating the design process to the quality of the designed final product[11]. Studies on multidisciplinary and interdisciplinary design have primarily stayed within the engineering domain[1,2], although one study described an interdisciplinary bioremediation sequence that included collaboration between engineers and biologists[12]. Another study of multidisciplinary collaboration focused on the research environment rather than the design environment, examining dialogue paths and finding that a small amount of faculty guidance for bridging knowledge gaps was a key factor for fostering collaboration among multidisciplinary graduate students[13]. Several other studies have also been performed focusing specifically on the BID design process. These studies have examined the cognitive aspects of analogical translation from biological to engineering domains as well as developing tools to aid in the translation[7,14-16].

This paper begins with a description of the course structure, followed by an explanation of the methods used in the study. The findings of the study are then described, and the paper concludes with implications for the design of courses that bring together disciplines outside the college of engineering.

Course Structure

Our institution offers a senior level undergraduate BID course that is cross-listed as a special toic in mechanical engineering, materials science and engineering, industrial and systems engineering, polymer textile and fiber engineering, and biology, which served as the research environment for this study. Enrolled in the course were 1 electrical engineer, 7 biologists, 13 biomedical engineers, 8 industrial and systems engineers, 13 mechanical engineers, and 3 materials science engineers.

At the beginning of the semester, the course consisted of introductory lectures about BID and the BID design process and also included discussions of 'found objects'. Found objects were homework assignments in which students identified natural objects relevant to a given topic, such as color in nature, and then researched and presented those objects to the rest of the class. The goal of the assignment was to give the students practice with identifying, researching, and understanding natural adaptations for given technical challenges. The bulk of the remainder of the course was spent alternating between guest lectures on various BID topics and continued discussions of new found objects. The guest lectures were in-depth presentations on each of several topics within BID, including optics, locomotion, sensing, and materials structuring. Guest lecturers came from various schools throughout the institute. The primary coordinator for the course was a professor in biology, with contributions made by myself - a postdoctoral student with a mechanical engineering background studying engineering education, and a graduate student in cognitive science who was studying the cognitive aspects of the analogical translation between engineering and biological domains. This trio will be referred to as 'the facilitators'.

The goal of the course was to give the students the opportunity to practice BID, so the primary assignment for the class was a semester-long design project, constituting 65% of the students' course grade. Students were given complete freedom to choose the topic, with the only requirement being that their project had to utilize principles taken from some biological source. The teams gave a proposal presentation in the middle of the semester on their project topic, and this allowed an opportunity to give guidance and a preliminary assessment to the students. The final product produced by the design teams was not to be a prototype, but rather a presentation and report that could be given to venture capitalists or a project manager requesting funding to move forward on the project. The final report was to describe the proposed design and how it could be made, and it was required to include quantitative analysis that assessed the feasibility and claimed advantages of the design. The purpose of this project format was to force students to consider economic and practical feasibility in their designs.

We placed students onto 4-5 person design teams at the beginning of the semester loosely based on common interests for the design project. We defined the groups such that a maximum of disciplinary diversity was achieved, with every team member hailing from a different department whenever possible. Designated office hours were scheduled during which the facilitators were all simultaneously available to help groups with their projects. Each project team was also assigned a faculty coordinator from the college of sciences or engineering with expertise in the area of the project topic.

Methods

I initially began my study desiring to identify and understand the problems that students encounter when placed on multidisciplinary design teams. To do this, I chose to perform an ethnographic study, which consisted of integrating onto two of the student design teams and attending the class as though I was a student. I operated as a contributing member of the teams while gathering data about the students' design process through participant observation. I took written notes of the events of all design meetings and wrote these into episodes, detailing the chronology of their design process. Informal interviews were also conducted with team members, and written artifacts from the design meetings were recorded.

As the course progressed, it became apparent that the most interesting challenges associated with multidisciplinary design did not occur within the student groups themselves but rather at the administrative level of the course. As the student design teams encountered challenges, I began to study the administration of the course and the guidance of the design teams by the facilitators. I was interested in identifying the sources of difficulty in bringing together experts from multiple disciplines to try to coordinate a design class consisting of students from multiple disciplines. In this aspect of the study, I focused on observing my own contributions as a facilitator, as well as the interactions among the facilitators, between the facilitators and the design teams, and the challenges encountered by a biology professor being the primary coordinator of a design class. Observations were made during class lectures, informal interviews with the biology professor, and during meetings between the facilitators and student groups.

Observations

When I began this study, I expected differences in technical knowledge to be the primary challenge encountered in this technical design course. While this may be true in multidisciplinary engineering design projects, this was not true when the included disciplines spanned into the college of science. Although some challenges were encountered that related to technical knowledge, the primary challenges encountered by the facilitators were education-related and centered on three things: the definition of 'good design' and how to encourage it, the relative priority the facilitators placed on working together as a multidisciplinary team, and awareness of student expectations and skills. The challenges associated with design and multidisciplinary education were observed primarily from the facilitators' guidance of the design teams, while the challenges associated with technical knowledge and student awareness were observed primarily through student observations.

Design Team Advisement – 'Good' Design

Over the course of the semester, the biology professor and I both expressed disappointment in the quality of the design ideas as we met with the student teams in the class. As we attempted to help the groups in response, our approaches were not only different, but were fundamentally opposed. It became apparent that she and I were trying to solve different problems, reflecting our own biases regarding which parts of the design process are most important. Proper design should go through each of several stages, shown in Fig. 1, often with iteration between the stages[17]. The first step should be problem definition, where the problem being solved is clearly defined and articulated. The second step should be brainstorming potential solutions to that problem, followed by selecting the best and most feasible solution. The last step in the process is physically realizing the chosen solution.

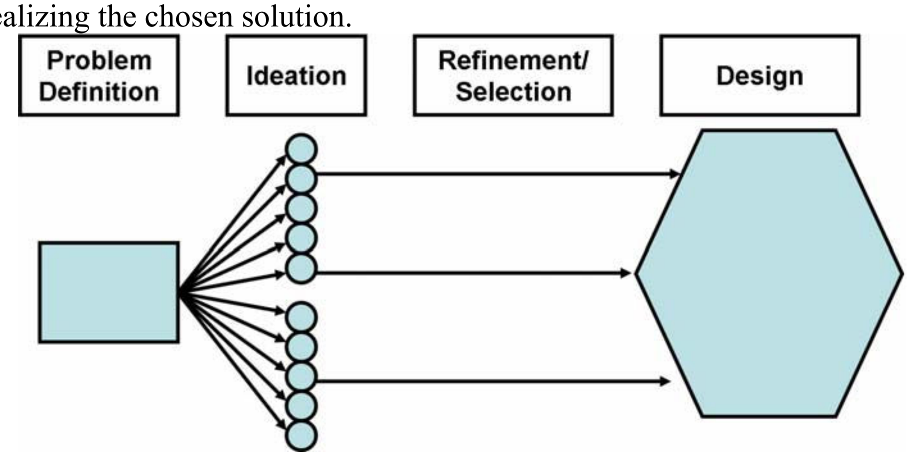

Figure 1. Design process schematic.

As a typical engineer, my own bias was towards the first and last steps: clearly identifying a problem, and feasibly realizing a solution, and the primary weakness I saw in the students' designs was that many of them had not clearly defined problems or considered whether their idea was economically or practically feasible. The primary weakness that the biology professor saw, however, was with the second step in the design process. She saw that many of the students were not thinking creatively and exploring the design space but rather fixating on single biological inspiration sources without exploring alternative possibilities. Thus, to help the students improve their projects, I tried to help them focus their problems, identify exactly what they were trying to solve, and identify weaknesses present in the extant solutions to the problems. Meanwhile, the biology professor tried to push the students into new directions, suggesting new problems to consider and new biological inspirations to use.

An example of this can be seen from our guidance of one particular student group that was interested in designing a device to help airplanes detect one another to prevent crashes. I encouranged the students to think about how planes currently communicate with one another and air traffic control, and what causes planes to crash. The biology professor, whose strength was thinking creatively and making connections, encouraged the students to think and read about various sensing mechanisms in the animal world as well as swarm and flock behavior in the hopes that such reading would stimulate new ideas, applications, and project topics. While I wanted to focus on refining the topic the students had chosen, she wanted to send them a journey of creativity, exploring new topics until they found a particularly interesting one.

Because we had different ideas about what constitutes 'design', our efforts to aid the students in their design projects were fundamentally opposed. While it was apparent that our efforts to aid the students were different, we failed to recognize that those efforts stemmed from different goals for the student projects, and it had not occurred to us that our fundamental goals might not be the same. Such difficulties highlight the possibility of unexpectedly encountering discipline-specific views of design that may be incongruous, and this may be especially relevant for collaboration between disciplines in engineering, industrial design, architecture, business, and the sciences.

The views of design were incongruous primarily because the design project had been developed from an engineering design perspective. A semester-long design project with a mid-semester proposal presentation is inherently geared towards steady progression along the design process for a single project topic. As the biology professor tried to steer the students into new directions, she found that they were generally unwilling to do so and instead fixated on their chosen topic regardless of whether their project was useful, interesting, feasible, or well-defined. Since creativity was the primary trait she wanted to see in the design projects, she underestimated the time and effort the students had invested both in the problem-definition step as well as in trying to understand the biological sources of inspiration they were intending to use. This invested time and effort over the course of the semester made the students resistant to changing topics.

A different project format could have been developed that would have allowed creativity and ideation without being incongruous with considering feasibility and problem-definition. In future iterations of the course, we will hope to reconcile the views of design by explicitly focusing on ideation at the beginning of the semester, and shortening the design project to the last third of the semester to still require accounting for practical and economic considerations.

Design Team Advisement – Multidisciplinary Facilitation

Although we structured the student teams to force multidisciplinary collaborations, we did not always embody this as a team of facilitators. Although all facilitators were present during office hours, whenever multiple student teams came to the office hours, the facilitators would split up, each working with a single team. Additionally, each group had individual assessment meetings after the mid-semester proposal presentations, and the only facilitator present at most of these meetings was the biology professor. However, the most productive advisory meetings with design teams occurred when both engineers and biologists were present to lend their respective expertise to the students simultaneously. The engineering expertise was essential for focusing the problem onto the right required behaviors, and the biological expertise was essential for identifying natural systems that contain those behaviors. Without an engineer present to help refine the questions from the students, the biology professor would often offer information that was only superficially related to the design group topic, for example giving information about structural cartilage in sharks to a group working on developing cushioning materials based on shock absorption in articular cartilage. Likewise, without the biology professor, the engineering facilitators, including myself, struggled both to identify natural systems that were relevant to the students' project topics and to translate the students' topics into questions relevant for biological systems. We worked well when we worked together but struggled individually, underestimating our own need to collaborate together as a multidisciplinary education team in running the class, with all facilitators contributing their own expertise[1,13,18].

Student Awareness

One challenge encountered by the facilitators had to do with our understanding of the abilities and motivations of the students outside of our background. In terms of student abilities, one encountered problem was that the biology professor had no way of knowing a priori that most engineering students have always had problems defined for them, and few, if any, would have much experience with defining their own problems[19,20]. Thus no explicit scaffolding or instruction was given to the students to emphasize the importance of clear problem definition in the design process, which contributed to the weaknesses in final design projects. Many student groups, including one of the teams on which I participated, began generating physical designs for their projects without ever having researched whether there was a need for their project. The group wanted to design a jet propulsion system that imitated jet propulsion in squids, and they began researching materials to use for artificial muscles in their design before having clearly identified the advantages such a system might offer over other types of jet propulsion.

Another challenge had to do with the students' level of ability to do academic literature research. BID requires detailed knowledge of biological systems in order to apply the principles of those systems into an engineering design setting, and such detailed knowledge can only reliably be found within academic journals. Most biology students had seen academic research articles and used databases from early on in their program, and the biology professor assumed the same was true for engineers. However, few engineers, other than the biomedical engineers, had ever used primary sources and most had little to no experience with searching databases for academic journal articles. Engineers, therefore, struggled to find information about the natural systems that they wanted to understand. Many relied on internet search engines to find information, which yielded only shallow information, and on those occasions when they did locate an academic article, they reported having difficulty understanding it. This problem was identified midway through the semester, and in response the biology professor gave a short presentation on using a common research database while I gave the students tips about reading journal articles. Although this helped somewhat, the need for acclimating engineering students to the practice of academic research is a necessary task for multidisciplinary education[21]. Because BID requires knowledge found primarily in journal articles, it may be an effective way of developing literature research skills in undergraduate engineering students.

The design biases of the facilitators also resembled the motivations of our students, and each of us was largely blind to the motivations of those students outside of our college, particularly over their relative concerns about feasability[22]. For the biology students in the class to see BID as useful, they primarily wanted to see how biological knowledge might be relevant to engineering problems. They had a preference for the brainstorming stage of design and were satisfied just with seeing potential uses of their biological knowledge. For the engineering students to see BID as useful, they had to see more than just potential uses of biological knowledge in design; they had to see that BID could result in designs that are feasible and superior to existing designs. Therefore, despite their struggles with problem definition, their preference was to carry the design process through to a completed design that solved an existing problem. Past studies of multidisciplinary design have noticed similar dichotomies between students from the colleges of science and engineering[22]. As I focused on discussing extant technologies and the importance of considering technical and economic feasibility, the less interested the biology students became. Meanwhile, as the biology professor focused on generating ideas without considering cost, time, or existing solutions, the less interested the engineering students became. Neither of us recognized how we were losing the attention of the students that were outside of our own disciplines.

Linguistic and Technical Challenges

Scientists and engineers brought together from different disciplines are generally aware that they have different knowledge bases but do not necessarily have a complete understanding of where their knowledge base does and does not overlap with that of their collaborators. Thus, I wanted to identify the knowledge that is specific to a given domain but that practitioners of that domain do not perceive to be domain-specific. This could be seen by observing which concepts were and were not explained in detail by guest lecturers and design team members. Although this topic could be the subject of an entire study, it did not prove to be of primary importance in the context of our BID class, so in this article I briefly describe only what seemed to be the most commonly encountered domain-specific topics.

The most common terms that biologists did not realize were domain-specific were generally related to biochemistry and biomaterials, including such terms as protein, enzyme, collagen, and functional group. This did not generally pose any challenges for design teams since few were focused on biochemistry. However, some of the journal articles assigned to the students as homework discussed biocatalysis and biomaterials, and the engineers had significant difficulty reading due to a lack of familiarity with the terms. The most common and significant concept that engineers did not perceive to be domain-specific was the subtle difference between the various material properties toughness, hardness, strength, and stiffness. This was especially relevant because many biological materials, including wood, spider silk, and ceramic composites, outperform human-made materials in some properties but not others, such as toughness but not stiffness[4,23,24]. In one guest lecture, a materials science professor was discussing the toughness of composite structures in nature, and a biologist suggested an application that required high stiffness rather than high toughness. Distinguishing between the material properties and the relevant applications is explicitly taught to mechanical and materials science engineers in introductory materials science and mechanics classes. Realizing that most non-engineers would have never encountered such distinctions, the materials science professor paused his lecture and gave an explanation of the different material properties and related them to an example stress-strain curve, as is generally done in introductory materials science courses.

Conclusions

Our multidisciplinary team of course facilitators anticipated differences in technical knowledge and were ready to work together to share this knowledge, but we underestimated the differences we had in our educational approaches and philosophies. The results of this study emphasize the importance of multidisciplinary course facilitators articulating their desired student outcomes, particularly when the facilitators come from different colleges. Additionally, facilitators should be aware of and communicate the expectations and motivations of the students within their respective disciplines, recognizing that students from different colleges may have fundamentally different expectations. Since part of the motivation for multidisciplinary design lies in the value of bringing together practitioners from different disciplines, this should be present at the administrative level courses as well, with each facilitator contributing according to her/his specialty. As a result of the difficulties inherent in teaching a multidisciplinary course, course coordinators should represent the disciplines in the class and should have equal input to the vision, goals, and expectations of the course, and having co-coordinators is preferable to a primary coordinator. Teaching a design course with multidisciplinary students requires a multidisciplinary educational approach.

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