Proceedings of the ASME 2015 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2016
August 21-24, 2016, Charlotte, North Carolina, USA

DETC2016-59661

SIGNIFICANCE, PREVALENCE AND IMPLICATIONS FOR BIO-INSPIRED DESIGN COURSES IN THE UNDERGRADUATE ENGINEERING CURRICULUM

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ABSTRACT

Engineers in the 21st century can no longer isolate themselves and must be prepared to work across disciplinary, cultural, political, and economic boundaries to meet challenges facing the US and the world. Recently, a greater emphasis is being placed on understanding social, economic and environmental impacts of engineered solutions. Undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries, but also communicate, transfer knowledge, and collaborate across technical and non-technical boundaries. One approach to achieving this goal is through introducing bio-inspired design in the engineering curriculum. Bio-inspired design encourages learning from nature to generate innovative designs for man-made technical challenges that are more economic, efficient and sustainable than ones conceived entirely from first principles. This paper reviews the literature pertaining to current approaches to teaching bio-inspired design in and engineering curriculum curriculum at different institutions as well as the essential competencies of the 21st century engineering. At James Madison University a Concept-Knowledge Theory instructional approach was adopted for teaching sophomore engineering design students bio-inspired design to foster many of the 21st century competencies. A pilot study was conducted to demonstrate that the 21st century competencies can be targeted and achieved. The results of study are presented, and the significance and implications of teaching bio-inspired design in an engineering curriculum are discussed.

INTRODUCTION

Innovative engineering design tools and methods are essential to creating new and better products and industries, and are also important for the US to maintain and sustain its global economic leadership. "Design Quality" is the main factor that differentiates one competing product from another. Companies such as Toyota, Apple, and Samsung are pioneers in positioning design as a key contributor to innovation. "Design Innovation" has been identified as an important learning approach for students in science, technology, and engineering disciplines by national organizations, like the National Science Foundation and the National Academy of Engineering, among others.

Undergraduate engineering programs that focus exclusively on engineering principles throughout the curriculum will not be able to train students to recognize interrelationships or be adaptive problem solvers. The connections within engineering may be obvious to students, or students might take it for granted that some aspects are similar. With bio-inspired design, however, many of the connections to be made between biology and engineering will not be obvious and making these connections will require critical thinking and investigation from multiple system levels and viewpoints, thus emphasizing systems thinking.

The knowledge base in biology has proven to be a useful resource for engineers searching for novel or creative approaches for solving complex design problems. Biological systems provide insight into sustainable and adaptable design, which has been used to inspire engineering innovation. Bio-inspired designs (sometimes referred to as biomimicry or biomimetics) are viewed as creative and novel solutions to human problems and are often efficient, economic, elegant and sustainable. Moreover, some bio-inspired designs, such as Velcro, have become so commonplace that it is hard to image life without them. Other imitations of nature now on the cusp of practical usefulness, such as artificial photosynthesis, could lead to enormous societal benefits including regional energy independence and reduced greenhouse emissions. The overarching motivation is not just to train students to explore the biological domain for solutions, but to have the cognitive flexibility, creativity, and adaptive problem solving skills to explore any contextual domain from which they might find solutions to complex, cross-disciplinary engineering problems. Teaching students about bio-inspired design improves their cross-disciplinary thinking skill which is among the essential competencies outlined in the Engineer 2020 Report and other organizations and researchers as discussed in the section below.

ESSENTIAL COMPETENCIES OF THE 21ST CENTURY ENGINEER

The Engineer 2020 report, ABET, and researchers have identified the essential competencies for engineers to be prepared to work across disciplinary, cultural, political, and economic boundaries to solve complex design challenges. Undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries, but also communicate, transfer knowledge, and collaborate across technical and non-technical boundaries. The competencies given below can be divided into two groups, task-specific and meta competencies. Task specific competencies are skill sets that defines how well-prepared graduates are to meet the workforce challenges that lie ahead based on their level of attainment [1]. Meta competencies are skill sets that enable graduates to function globally while meeting technical demands, have the cognitive flexibility to think about the whole system at different levels of fidelity and in different time scales, and transfer task-specific skills to new challenges or tasks they have not encountered before [2]. While not an exhaustive inventory of the literature on engineering competencies, the following lists outline the essential competencies for the 21st century engineer from three key perspectives.

Competencies outlined in the Engineer 2020 report

The Engineer 2020 report is an initiative by the National Academy of Engineering (NAE) to define the attributes required for an engineer in 2020 and actions that may be taken to promote achievement of these attributes. The vision states that engineering graduates [3]:

- will possess strong analytical skills, like engineers of yesterday and today
- will exhibit practical ingenuity
- will be creative
- will be good communicators
- will master the principles of good business and management
- will understand the principles of leadership and be able to practice these principles
- will have high ethical standards and a strong sense of professionalism
- will possess a complex attribute described as dynamism, agility, resilience, and flexibility
- will be life long learners.

Competencies outlined by ABET

The Accreditation Board for Engineering and Technology (ABET) holds engineering schools accountable for the knowledge, skills, and professional values that engineering students acquire in the course of their education. In order to do this, ABET established the following set of student outcomes that each program must demonstrate [4]:

- Outcome a: "an ability to apply knowledge of mathematics, science, and engineering"
- Outcome b: "an ability to design and conduct experiments, as well as to analyze and interpret data"
- Outcome c: "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability"
- Outcome d: "an ability to function on multi-disciplinary teams"
- Outcome e: "an ability to identify, formulate, and solve engineering problems"
- Outcome f: "an understanding of professional and ethical responsibility"
- Outcome g: "an ability to communicate effectively"
- Outcome h: "the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context"
- Outcome i: "a recognition of the need for, and an ability to engage in life-long learning"
- Outcome j: "a knowledge of contemporary issues"
- Outcome k: "an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice"

Competencies outlined in analysis to support engineering innovation

Siddique et al. developed a competency-based approach to personalized education for 21st century engineers [5-8]. In their approach, the meta-competencies to support innovation were identified with acknowledgement that students will build on some competencies and add new ones as they progress through the curriculum. Built on a set of competencies complied by various educators and researchers, the following is a list of meta-competencies that need to be developed by future engineers to support innovation [6]:

Ability to Manage Information

- Ability to gather, interpret, validate and use information
- Understand and use quantitative and qualitative information
- Discard useless information

Ability to Manage Thinking

- Ability to identify and manage dilemmas associated with the realization of complex, sustainable, socio-techno-eco systems
- Ability to think across disciplines
- Holistic thinking
- Conceptual Thinking
- Ability to speculate and to identify research topics worthy of investigation
- Divergent and convergent thinking
- Ability to engage in critical discussion

- Identify and explore opportunities for developing breakthrough products, systems or services
- Ability to think strategically by using both theory and methods

Manage Collaboration
- Ability to manage the collaboration process in local and global settings
- Ability to create new knowledge collaboratively in a diverse team
- Competence in negotiation
- Teamwork competence

Manage Learning
- Ability to identify the competencies and meta-competencies needed to develop to be successful at creating value in a culturally diverse, distributed engineering world
- Ability to self-instruct and self-monitor learning
- Ability to interact with multiple modes of learning

Manage Attitude
- Ability to self-motivate
- Ability to cope with chaos
- Ability to identify and acknowledge mistakes and unproductive paths
- Ability to assess and manage risk taking

Comparison and synthesis of the different perspectives on competencies for the 21st century engineer reveals the following common themes.
- Holistic, Critical thinking
- Complex, Multidisciplinary problem solving
- Creativity
- Communication across disciplines
- Understand impact in global, economic, environmental, and societal contexts
- Collaboration in a multidisciplinary team
- Self-regulated learning
- Flexibility and agility
- Global Awareness

Students learning through bio-inspired design have the potential to meet all of these competencies. Bio-inspired design is inherently interdisciplinary and blends information from biology, engineering, physics, mathematics, architecture, and design and consequently fosters the first four competencies. With communication also including scientific literacy [9]. Understanding impact is fostered through comparing natural to engineered solutions and recognizing that all materials, forms, and processes of natural systems have a purpose (a function) and sometimes multiple purposes as well as projects that require designing for those outcomes. Bringing together teams of people across disciplinary boundaries, within and outside engineering, fosters innovation through the diversity of thought and communication. While inter-professional teams are the strongest, there maybe institutional limitations that prevent such teams. Learning, flexibility, and agility are fostered through open-ended questions and projects that require the student to define the problem and inspiring biological system. The final competency can be fostered through considering the biological systems in regional areas across the globe or working with teams abroad.

In the current context, it is widely recognized that most students that go into engineering have high school level training in biology. Adding biomimicry into the engineering curriculum encourages students to utilize and build off their prior knowledge, which fosters making connections and recognizing interrelationships across STEM disciplines[10, 11]. Moreover, requiring knowledge transfer across domains as well as organizing that knowledge into logical constructs helps to develop future flexibility and adaptive expertise that will facilitate innovation and efficiency[12, 13]. These competencies have also been identified as critical key skill areas for engineers by the Partnership for 21st Century Skills [14] and the Assessment and Teaching of 21st Century Skills working group [15]. Instruction on bio-inspired design concepts will help engineering colleges achieve a number of the recommendations made by the National Academy of Engineering in reference to educating the engineer of 2020 [3], as well as ABET student outcomes c, d, e and h [4] and foster competencies that support engineering innovation.

TEACHING BIO-INSPIRED DESIGN

In response to the increased emphasis on cross-disciplinary thinking skills and adaptive and sustainable designs by professional societies, industry and today's global marketplace, engineering colleges in the United States and abroad are increasingly expanding the scope and focus of their curricula to include bio-inspired design topics and projects that expand systems thinking skills, and has been integrated at the module, project, or course levels [10, 11, 16-29]. While instruction in bio-inspired design is quite common in engineering programs at the graduate level, it is exciting to note that bio-inspired design instruction is also being incorporated into curricula at the undergraduate level as described in Table 1. It is important to note that this list is not meant to be exhaustive but rather to emphasize that it is feasible to creatively integrate bio-inspired design into the undergraduate curriculum from the sophomore to senior levels. The following sub-sections detail how bio-inspired design instruction has been integrated into undergraduate engineering curricula.

Courses in Bio-inspired Design

Several institutions including Georgia Tech (Center for Bio-inspired Design), Arizona State University, Northern Arizona University [30], University of St. Thomas [31], Duke University, University of Delaware, and others have been engaging in innovative research and developing educational materials (environmental ethics, course for artists, etc.) related to biomimicry. The instructional resources and activities need to be tailed for systematic use in courses such as design and simulations in engineering as well as non-engineering disciplines. The Biomimicry Institute (www.biomimicryinstitute.org) and teachEngineering.org are also promoting biomimicry concepts by giving workshops and training to academic faculty and K-12 teachers.

Multiple institutions offer semester long engineering courses in bio-inspired design or interdisciplinary courses that bring together students from STEM and art. Probably the most well known institution is Georgia Tech, which offers multiple courses and a certificate through the Center for Bio-inspired Design [32-34]. The undergraduate interdisciplinary course is co-taught by faculty from biology and engineering, and admits junior and senior level students from all fields of engineering and biology. Two processes for bio-inspired design, problem-driven and solution-driven, are taught in the course, and analogies are formed through functional decomposition similarly to functional modeling in engineering design [33]. More recently, the four-box method that identifies function, operating environment, constraints, and performance criteria as dimensions for matching biological analogues with the design problem has been implemented [35]. Students work in interdisciplinary teams on assignments and projects throughout the course. Honors-level undergraduate courses similar to the one at Georgia Tech have been offered at institutions such as Virginia Tech.

The mechanical engineering department at Montana State University offers a senior level technical elective on bio-inspired engineering [26]. The course covers relevant bio-inspired design and engineering design processes with a focus on structures and materials from both nature and engineering. The practices taught in the course include reverse engineering and tabulating a variety of relationships. Thus, the focus is more on comparison than innovation. Texas A&M is currently developing an undergraduate course to introduce interdisciplinary engineering students to multiple methods of bio-inspired design [22]. The course will be an elective in the mechanical engineering curriculum that focuses on breath of approach rather than depth, exposing students to the state-of-the-art in bio-inspired design research tools and methods. At the Olin College of Engineering, all students take a course that introduces bio-inspired design in their first semester. The course is called Design Nature and is an introduction to the engineering design process that also weaves in concepts from nature. Students complete individual and team projects in the course. Similarly, all first year engineering students at the University of Calgary are introduced to biomimicry in their design and communication course.

At Kettering University, in the Industrial and Manufacturing Department, biomimicry is integrated into an ergonomics course through problem-based learning [19]. Students work individually on projects using the Biomimicry Innovation Tool, which blends aspects of problem based learning, innovation, biomimicry, and ergonomics into a single student experience. They present their bio-inspired concept at the end of the course. The University of Maryland offers a course in biomimetic robotics as a senior elective in the mechanical engineering program [17]. Students study biological locomotion and how it can inspire efficient mechanisms of motion.

It is evident from reviewing the Bio-inspired Design course offerings at various institutions listed in Table 1 either as electives or regular courses, students are being exposed to 21st century competencies, specifically related to collaboration and creativity and innovative solutions to open-ended design problems. In order to systematically evaluate all of the 21st century competencies in various courses at different institutions, a more rigorous approach to surveying the students is required.

Bio-inspired Design Modules and Projects

Bio-inspired design concepts and examples have been used by several institutions to educate students on design innovation and as another source of design inspiration. Institutions include Oregon State University, University of Georgia, James Madison University, Purdue University, Clemson University, Penn State University-Erie, University of Maryland, Indian Institute of Science, University of Toronto and Ecole Centrale Paris to name a few. Often the instruction is across less than four lectures, which reduces the burden of integration into existing courses. These institutions also require engineering students to complete assignments or a project involving bio-inspired design to practice the technique and demonstrate its value. Integration occurs at the freshman through senior levels, in a variety of departments, and primarily depends on when engineering design is offered in the curriculum. Consequently, varying levels of instruction and support are provided to the students, and many rely on the resources provided by the Biomimicry Institute, such as the database AskNature.org. This points to the lack of engineering-focused, evidence-based instructional resources available to faculty that wish to integrate bio-inspired design into their courses.

OBERVATIONS ON THE STATUS OF BIO-INSPIRED DESIGN COURSES IN UNDERGRADUATE ENGINEERING CURRICULA

As can be seen from the discussion presented in the previous section, it is interesting that universities and institutions within the United States and aboard are beginning to recognize that it is important to expand undergraduate engineering curricula and are offering courses, modules and project based learning activities with an emphasis on bio-inspired design thinking. Implementing biomimicry concepts into engineering design curriculum presents a unique opportunity to incorporate fundamental curiosity driven and technology perspectives and involve collaborations from multiple disciplines. In addition, faculty from various disciplines will have the opportunity to engage in a collaborative teaching environment and share valuable experiences and insights. Moreover, anecdotal evidence suggests that students find bio-inspired design exciting, as it offers relevance to professional practice as well as an effective hook to frame complex, cross-disciplinary problems. As an example, one of the student groups in a sophomore design course at the University of Georgia, took inspiration from the

Table 1. A sampling of bio-inspired courses at US Universities and Abroad

University	Institute/ Department	Course Level	Emphasis
United States Institutions			
Georgia Tech	Center for Bio-inspired Design	Junior and Senior level students in engineering and biology	Problem driven and solution driven approaches to bio-inspired design; four box method for matching biological analogies to design problems
Virginia Tech	Industrial Design	Honors undergraduate engineering students	Problem driven and solution driven approaches to bio-inspired design; Biomimicry principles, concepts, and methodologies
Montana State University	Mechanical Engineering	Technical Elective for Seniors	Comparison of structure and materials from nature and engineering
Kettering University	Industrial and Manufacturing Dept.	Senior Level	Biomimicry concepts integrated into an ergonomics course; use Biomimicry Innovation Tool
University of Maryland	Mechanical Engineering	Elective for seniors	Biological locomotion as an inspiration for designing efficient mechanisms for motion
Olin College of Engineering	College of Advancing and Professional Studies	Required course for first year students	Design process using biomimicry principles, concepts, and methodologies
Texas A & M University	Mechanical Engineering	Elective for seniors	Research methods and tools for bio-inspired designs
International Institutions			
University of Calgary	Schulich School of Engineering	First year common core course	Design using natural proportions (the golden selection) and biomimicry as a design approach
Imperial College London	Mechanical Engineering	Elective for seniors	Structural analysis of forms from nature and engineering

Namibian beetle, specifically in regards to how it harvests moisture from the air by first getting it to condensate on its back and storing it, and designed a system to collect water using metal sheets and tubing for filling dog bowls or watering crops. Courses incorporating bio-inspired design into engineering curricula, might help students to think innovatively in a multidisciplinary fashion. Another advantage to including bio-inspired design courses in undergraduate engineering curricula is that bio-inspired design touches on many areas of engineering including electrical, mechanical, materials, biomedical, chemical, manufacturing and systems, which makes it applicable in a wide range of engineering programs, from discipline specific to general ones. Thus, there are several opportunities to foster the nine distilled competencies of 21st century engineers in a variety of institutional settings through bio-inspired design with engineering design courses being the most advantageous. Many of the current offerings are at the senior level, which provides the advantages of students being able to apply complex engineering theories, work efficiently in teams, communicate well, perform research, and think abstractly and holistically. It is expected that students are meeting the ABET outcomes by their senior year, which can allow for a richer course experience, but may not carry over into their professional work. On the other hand, introductory level courses in the first year expose students to a new way of thinking that could be reinforced throughout their college coursework thus embedding the approach in their problem solving process and will foster some of the nine distilled competencies. Ideally, students would apply bio-inspired design throughout an engineering curriculum to ensure the competencies are met.

Finally, the authors believe that teaching multidisciplinary design through biomimicry will be vital to promoting future innovation in engineering design and will also attract women and minority students with diverse backgrounds to pursue science and engineering fields. Curricula that are more practically and socially relevant, such as focusing on skill development related to engineering practice, have shown to attract more women and minorities [36-39].

While bio-inspired design is rapidly gaining in popularity in engineering courses, little is known about how to teach it or support students in the discovery and knowledge transfer processes that enable design innovation to occur. There are now more calls for research identifying and establishing best practices for teaching bio-inspired design concepts at the undergraduate level. We are currently using support from the National Science Foundation to develop instructional resources that can help to effectively scaffold students to transfer knowledge across disciplinary boundaries and train engineers in cross-disciplinary thinking. We propose to use Concept-Knowledge (C-K) Theory [40-43] in developing instructional resources, as it is a well-established approach for integrating multiple domains of information and facilitating innovation through connection building. The instructional resources are designed to foster the competencies of holistic, critical thinking; complex, multidisciplinary problem solving; creativity; communication across disciplines; understand impact in global, economic, environmental, and societal contexts; self-regulated learning; and flexibility and agility. Through the design, implementation, and evaluation of our instructional resources for bio-inspired design, we will not only create evidence-based resources, but also discover new and effective teaching methods, which will enhance the pedagogy of bio-inspired design in an engineering curriculum.

BIO-INSPIRED DESIGN PILOT STUDY AT JAMES MADISON UNIVERSTIY

During a pilot study at James Madison University, the C-K theory instructional approach was adopted for teaching a sophomore engineering design class to specifically address how the 21st century competencies can be targeted and achieved.

Pilot Study Approach

To implement the C-K theory instructional approach a bio-inspired design teaching module, learning activity, and assignment that incorporated a C-K mapping template with guidelines was created and integrated into the course during the topic of concept generation and introduced as a creative method for design. All assignments in the sophomore design course tie to a year-long course project of developing a human powered vehicle for a client in the community that has cerebral palsy, including the bio-inspired design assignment. To integrate bio-inspired design into the human powered vehicle design project each member of a team applied bio-inspired design to a different sub-system (e.g., propulsion, steering, braking) of their design to showcase a variety of design problems and analogies that enable bio-inspired design. All students completed the C-K mapping template three times, twice in class as part of a learning activity to understand the process of discovery and again in their assignment to scaffold application to the human powered vehicle.

The developed teaching module introduces bio-inspired design as a design philosophy and provides several examples of how biological systems were used as inspiration for innovative solutions. Students learn about the two major paths to a bio-inspired de-sign, biology-driven and problem-driven, as well as how analogies are used to assist with transferring the knowledge from biology to engineering. For the purposes of scaffolding the sophomore engineering de-sign students in their application of bio-inspired de-sign, two problem-driven examples using C-K theory were provided with accompanying learning activities. One problem-driven example and learning activity focused on the hingeless facade shading mechanism, Flectofin®, inspired by the bird-of-paradise flower [44]. Shading buildings with irregular geometries is very difficult since most sun protection systems were developed for planar façades and include the use of hinges. The pollination mechanism of the bird-of-paradise flower offers inspiration based on the elastic kinematics of plant movements. After the initial problem is explained, students are provided the partially filled in template shown in Figure 1 to complete during the explanation of the example. This scaffolds the students through the C-K theory mapping process. Students are walked through the thought processes and analogies of the discovery process for arriving at a bio-inspired solution using the C-K theory framework.

The developed assignment that compliments the teaching module and learning activities includes three parts: 1) complete the C-K mapping template for a human powered vehicle subsystem, 2) use the sketches in the C3 level of the template along with the team generated morphological matrix to create a full human powered vehicle concept, and 3) a W/H/W re-flection essay answering three questions about the content and process. The W/H/W reflections require learners to reflect on and respond to three questions: What did I learn?, How did I learn it?, and What will I do with it? These three prompts structure reflection so that learners focus on concepts, knowledge and skills, processes, and utilization/generalization/sustaining of learning. The W/H/W reflections provide formative snap-shots of learning and application that the learners are making as they progress through the material.

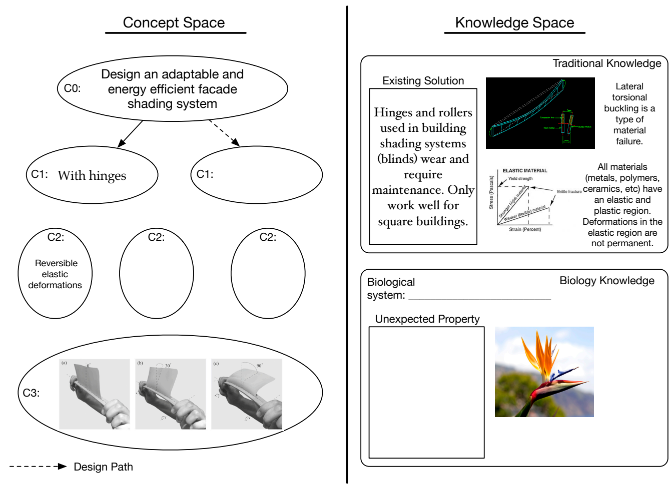

Figure 1: Template for Hingeless Facade Shading Mechanism Learning Activity

Pilot Study Analysis

Analysis of the W/H/W reflection questions aims to identify which 21st century competencies were achieved by incorporating bio-inspired design education in an engineering design course. Fifteen (65%) students consented to participate in the research. Transcriptions of the reflection questions for consenting participants were de-identified and analyzed using qualitative content analysis. Qualitative content analysis identifies themes in the student reflections. This method involves reducing participants' comments to their smallest meaningful unit, coding these units, identifying categories for these codes, and then finally identifying themes from the categories [45]. The reflection statements resulted in 206 (108 for content questions and 98 for process questions) unique/coded meaningful units. Multiple themes and categories emerged for each question based on coded meaningful units. Themes for each reflection question including the number of student responses that support that theme, and the distilled competencies that the instructional resources were intended to foster are given in Table 2.

Table 2. Mapping of Reflection Questions to Themes and Competencies

Reflection Question	Themes (n = supportive categories)	Competencies Addressed
What did I learn about the content?	• Valued what can be learned from nature and biology (17) • In-depth understanding of chosen biological system (14) • Cross-domain linkages (11) • Biology is not always applicable (4)	• holistic, critical thinking • self-regulated learning • communication across disciplines
How did I learn the content?	• Scholarly or external resources (31) • Course learning resources (4)	• self-regulated learning • communication across disciplines
What am I going to do with the content?	• Apply to immediate problem – course project (16) • Facilitate a future design path (11)	• flexibility and agility • complex, multidisciplinary problem solving • creativity
What did I learn about the process?	• Valued the inclusion of biology in engineering design (22) • Recognized knowledge transfer between domains for problem solving is possible (17) • Bio-inspired design is not always applicable (3)	• holistic, critical thinking • communication across disciplines • understand impact in global, economic, environmental, and societal contexts
How did I learn the process?	• Course learning resources (20) • External or other resources (13)	• self-regulated learning • communication across disciplines
What am I going to do with the process?	• Facilitate a future design path (20) • Apply to immediate problem – course project (3)	• flexibility and agility • complex, multidisciplinary problem solving • creativity

Focusing on the content (biology knowledge), students learned that biological systems are surprising complex but have attributes that can easily be applied to design problems. Recognition that nature has a lot to offer resulted in valuing what can be learned from biological systems. Conversely, a few students concluded that biological knowledge is not always applicable to the design problem. Both of these themes as well as forming cross-domain linkages link to the competency of critical thinking as students had to analyze the information they were finding and manage their own thinking about the information. The competencies of self-regulated learning and communication across disciplines link strongly to the themes of students learning about biological systems by engaging with scholarly resources through independent research, and forming cross-domain linkages as students had to dive deeper into the literature than just looking at the pictures to understand how the biological system relates to their chosen problem. Similar trends were observed for what students learned about the process of bio-inspired design. Critical thinking was exhibited in recognizing the value (or not) of including biological inspiration in a design process and that the process facilitates knowledge transfer between the domains that results in solutions to engineering problems. Communication across the disciplines is also evident in the recognition of knowledge transfer across domains. Understanding impact in a broader context was evident as looking to nature for inspiration resulted in students finding possible solutions that they thought were more sustainable than the existing engineering solution.

The competencies of self-regulated learning and communication across disciplines directly relates to how students learned the content and process. In both cases, internal resources (the instructional materials) and external resources (scholarly works and websites) were used to learn the content and process. It is not surprising that external resources were heavily used for learning the biology knowledge as it was required for students to identify and learn about the inspiring biological system independently. Whereas all the resources for learning the process were modeled in class and provided for the assignment.

With respect to what the students are going to do with the content and process it was not surprising to see the main trends of application to the course project and future opportunities. Creativity as well as flexibility and agility are expressed in the application of the analogically distant information (biology) to the target problem in engineering, and generally gaining a new perspective when designing. The competency of complex, multidisciplinary problem solving is embedded in the application of bio-inspired design to a specified problem, and it is encouraging to see the trend of wanting to use bio-inspired design when designing or solving engineering and non-engineering problems in the future.

One student expressed that learning about biology helped in gaining further knowledge about a specific sub-system of the human powered vehicle. Similarly, two students expressed that they would use existing biology knowledge to help understand engineered components and systems. Meaning, the students learned more about engineering through biology. This unanticipated result points toward the significance of teaching bio-inspired design in an engineering curriculum. Teaching bio-inspired design in an engineering curriculum using interdisciplinary approaches will not only develop competencies of the 21st century engineer but also enable undergraduate students to become change agents and promote a sustainable future.

Pilot Study Limitations and Future Work

Limitations to this pilot study include the low sample size, implementation at a single institution, and the use of student self reported data. To increase sample size numbers all sections of the JMU sophomore engineering design course will be asked to participate in the study. Grouping qualitative data from the six student reflection question statements to create themes was challenging as some responses seemed to be for a different question. Future work also includes implementation plans for the C-K Theory instructional materials in a sophomore engineering design course at the University of Georgia. Through the creation of rubrics for analysis of the student generated artifacts (C-K mapping template and concept) comparison of student work across institutions will be possible, and it will provide an objective measure to judge transferability of instructional materials from JMU to UGA, or visa versa.

CLOSING REMARKS

It is well known that engineering involves integrating broad knowledge towards some purpose, generally to address a need or solve a problem. As we move into a global future, undergraduate education will need to prepare engineers to work in multidisciplinary, interdisciplinary, and transdisciplinary environments [46]. Undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries, but also communicate, transfer knowledge, and collaborate across technical and non-technical boundaries. One approach to achieving this goal is teaching biomimicry or bio-inspired design in the engineering curriculum [47]. Cross-disciplinary instruction in biomimicry will increase engineering students' cognitive flexibility, creativity, and adaptive problem solving skills. Biomimicry also touches on many areas of engineering including electrical, mechanical, materials, biomedical, chemical, manufacturing and systems, which makes it applicable in a wide range of engineering programs, from discipline-specific to general ones.

Teaching bio-inspired design in an engineering curriculum meets many of the competencies of the 21st century engineer, which are vital as we move into a global future. We demonstrated through a pilot study that many of the essential competencies such as thinking critically and making judgments; solving complex, multidisciplinary open-ended problems; communicating and collaborating across disciplines; making use of knowledge and information in creative ways; engaging in life-long learning; and transferring problem solving skills across a variety of problems and contexts can be fostered in an engineering curriculum through bio-inspired design. We believe these are transferrable skills that will enable future engineers to be successful in the global workforce and help them tackle the cross-disciplinary challenges that lie ahead. Furthermore, teaching engineers bio-inspired design has the possibility to not just train students to explore the biological domain for solutions, but to have the cognitive flexibility, creativity, and adaptive problem solving skills to explore any contextual domain from which they might find solutions to complex, cross-disciplinary engineering problems.

We reviewed the literature to show growing support for incorporating bio-inspired design concepts in the undergraduate curriculum and presented some of the engineering programs in the United States and abroad that are already incorporating bio-inspired design courses into their curricula for students from the sophomore to junior levels. While progress is being made in expanding existing engineering curricula to include bio-inspired design concepts, there is still a need to establish best practices for teaching bio-inspired design at the undergraduate level. It is our belief that this research will stimulate additional interest in this area and contribute to developing a database of evidence-based instructional resources, as well as new and effective teaching methods, which will enhance the pedagogy of bio-inspired design in the engineering curriculum.

ACKNOWLEDGEMENTS

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. This material is based upon work supported by the National Science Foundation under Grant No. 1504612.

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