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Enhancing the Pedagogy of Bio-inspired Design in an Engineering Curriculum

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Abstract

In addition to providing the technical expertise required to solve 21st century problems, the engineers of 2020 will be expected to adapt to a continuously evolving environment while operating outside the limits of their discipline and remaining ethically grounded. Their undergraduate training must therefore be designed to nurture engineers to transcend traditional disciplinary boundaries, and to communicate, transfer knowledge, and collaborate across technical and non-technical boundaries. One approach to this challenge is to incorporate biomimicry or bio-inspired design into the engineering curriculum. Our research aims to create instructional resources that provide exposure to the abundance of design examples that can be found in nature, and scaffold the discovery and knowledge transfer processes so that those natural designs can be used to inspire engineering solutions. This research is expected to produce knowledge that will improve student learning, STEM literacy, cross-disciplinary thinking, and innovation. Bio-inspired design is also expected to enhance the diversity and inclusion of ideas, and to attract women and minority students with diverse backgrounds to pursue STEM fields. Its ultimate benefit, we hope, will be to fuel the design innovations needed to create a more sustainable future for humankind.

1. Introduction

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, engineers can no longer isolate themselves and must be prepared to work across disciplinary, cultural, political, and economic boundaries. Every day, engineers are confronted with complex challenges that range from personal to municipal to national needs[1]. The ability for future engineers to work in multidisciplinary, interdisciplinary, and transdisciplinary environments will be an essential competency[2]. With greater emphasis being placed on understanding social, economic and environmental impacts of engineered solutions, the cognitive flexibility to think about the whole system at different levels of fidelity and in different time scales has also become essential[3, 4]. Undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries, but to 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 an engineering curriculum[5]. Although nature has consistently provided inspiration for engineering solutions that are more economic, efficient and sustainable than ones conceived entirely from first principles[6], how to incorporate biomimicry into educational practices remains a challenge.

Cross-disciplinary instruction in biomimicry has great potential for developing cognitive flexibility, creativity, and adaptive problem solving skills. Providing students with open-ended biomimicry-related problems throughout the curriculum is an important common thread for tying course material together and for teaching students to solve complex problems by integrating knowledge from different disciplines. This work requires students to identify and formulate specific problems to solve, which are fundamental to the engineering profession[7]. Having to retrieve and transfer knowledge from domains outside of engineering forces students to adapt to unfamiliar languages and content formats (which helps develop non-technical skills) and positions them to apply the biological information intelligently to engineering problems (which helps develop technical skills). Additionally, biomimicry touches on many areas of engineering including electrical, mechanical, materials, biomedical, chemical, manufacturing and systems, which makes it applicable across both discipline-specific and general engineering programs.

Incorporating biology into complex engineering problems will create a new context for undergraduate students to apply knowledge that they already have. Most students that go into engineering have some 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[8, 9]. 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[10, 11].

We also believe that using biomimicry to teach multidisciplinary design will attract women and minority students with diverse backgrounds to pursue science and engineering fields. Studies show that women and underrepresented minorities are drawn to curricula, courses, and instructional strategies that are integrated, emphasize broad or systems thinking, and facilitate connection building across courses or disciplines[12-14], and that women have an intellectual preference for topics that draw on multiple fields[15, 16]. Women are also attracted to curricula that are more practically and socially relevant, including ones that focus on skill development related to engineering practice[13, 17-19].

Showing engineering students the significance and utility of bio-inspired design is easy. Teaching them how to do bio-inspired design without requiring them to be fully trained as biologists is much more difficult. Teaching bio-inspired design in an engineering curriculum has traditionally relied on either the ad hoc application of biological inspiration or research methods and tools that are tied to specific engineering design methodologies. Typically within the classroom, a tool or method is presented with an example that illustrates the technique and students are expected to practice the inherent knowledge transfer steps required to understand the underlying principle, which are typically lumped together under the term principle extraction. Much less is known about how to effectively guide students in the knowledge transfer steps that are so crucial to moving between the engineering design space and the biology space. Students are set up to make the creative leap across these spaces, but are not supported in the actual leap. Thus, analogy use/misuse, mapping, and transfer are frequently cited as the major challenges with teaching bio-inspired design to engineers[20-28]. This is an important gap in our teaching tool kit since effective navigation between the engineering design and biology spaces is essential for students to make the connections that facilitate innovative design and increase their cognitive flexibility, creativity, and adaptive problem solving skills[29]. ***The goal of our research is to fill this gap with new evidence-based instructional resources.*** Before outlining our plan to meet this goal, we provide a brief summary of the importance of bio-inspired design in design innovation and a survey of existing undergraduate engineering curricula that teach biomimicry.

1.1 The Importance of Bio-inspired Design for Design Innovation

Innovative engineering design and simulations are essential to creating new and better products and industries, and are 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. Toyota, Apple, and Samsung are pioneers in positioning design as a key contributor to innovation. These and other creative companies are increasingly emphasizing the importance of connecting design to customers' emotions and needs, and of constructing maps that show the path to innovation. "Design Innovation" has been likewise identified as an important skill for students in science, technology, and engineering disciplines by national organizations like the National Science Foundation and the National Academy of Engineering.

Real-world problems are rarely defined along specific disciplinary lines and innovation occurs when those lines are crossed. Biological systems have always been a source of inspiration for engineers, and many bio-inspired designs (sometimes referred to as biomimicry or biomimetics) that were developed simply as novel solutions to specific man-made technical problems are now recognized for being exceptionally efficient, economic, elegant and sustainable. Some, such as Velcro, have become so commonplace that it is hard to image life without them. Other imitations of nature that are 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.

1.2 Teaching Bio-inspired Design

Instruction in bio-inspired design is becoming more common in engineering programs in the United States and abroad, and has been integrated at the module, project, and course levels[8, 9, 20, 23-25, 27-36]. Though it occurs primarily in graduate level design courses, bio-inspired design instruction is now being integrated into undergraduate curricula. Multiple institutions offer semester long 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[37-39]. 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[38]. 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[40]. 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, and will be offered at James Madison University in the Spring 2017 semester.

The mechanical engineering department at Montana State University offers a senior level technical elective on bio-inspired engineering[23]. 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 that are taught 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[34]. 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.

At Kettering University, in the Industrial and Manufacturing Department, biomimicry is integrated into an ergonomics course through problem-based learning[32]. 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[28]. Students study biological locomotion and how it can inspire efficient mechanisms of motion.

Bio-inspired design concepts and examples have also been used by many institutions to educate students on design innovation and as another source of design inspiration. These include Oregon State University, University of Georgia, James Madison University, Purdue University, Clemson University, Penn State University-Erie, University of Maryland, University of Calgary, Indian Institute of Science, University of Toronto and Ecole Centrale Paris. 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 depends primarily 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 that are available to faculty who wish to integrate bio-inspired design into their courses.

2. Research Approach

Our plan to develop and test instructional resources for transferring knowledge between biology and engineering is outlined in Table 1.

Table 1: Plan for incorporating biomimicry into design innovation

Objective 1	Create and disseminate evidence-based instructional resources:
	a. Design instructional resources that help students to identify characteristics of engineering design problems that enable bio-inspired design (making the leap from engineering to biology).
	b. Design instructional resources that facilitate the analogy mapping and transfer process of bio-inspired design (making the leap from biology to engineering).
	c. Disseminate the evidenced-based instructional resources through publications and global educators networks.
Objective 2	Evaluate the learning impact of the evidence-based instructional resources:
	a. Assess student engagement in learning.
	b. Assess student ability to recognize and formulate interrelationships across disciplinary boundaries.
	c. Assess student ability to create bio-inspired designs.

2.1 Accomplishing objective 1: Creating and disseminating instructional resources:

Salgueiredo[41] summarizes the various theoretical frameworks available for understanding bio-inspired innovative design, which include general design theory, axiomatic design, coupled design process and Concept-Knowledge (C-K) design theory. From this summary, we have identified C-K design theory[42-44] as a particularly useful tool for developing instructional resources to scaffold engineering students in the critical thought processes of bio-inspired design. C-K theory (Figure 1) does not rely on a particular engineering design approach. Rather, it relies on the process of discovery, which is key to bio-inspired design as well as design innovation. Concept-Knowledge theory is also adaptive and generalizable across scientific domains, which makes it amenable to a wide range of engineering problems as well as programs. Finally, C-K theory is particularly useful for understanding how biological knowledge can be used to expand and navigate between the "concepts" and "knowledge" spaces at the interface between natural and engineered systems.

C-K theory, which was introduced by Hatchuel and Weil[42-44], integrates creative thinking and innovation by utilizing two spaces: (1) The knowledge space (K) – a space containing propositions that have a logical status for the designer; and (2) The concepts space (C) – a space containing concepts that are propositions or groups of propositions that have no logical status (i.e. are undetermined) in *K*[42-46]. This means that when a concept is formulated, it is impossible to prove that it is a proposition in *K*. Rather, concepts generate questions, and the research to answer those questions will generate new knowledge that will provide new attributes for new concepts. The wider your initial knowledge is, the higher the number of feasible concepts. However, the final result of the concept generation process is initially unknown. The design path is defined as a process that generates concepts from an existing concept or transforms a concept into knowledge.

Although specific tools are not embedded, C-K theory has shown to reduce fixation and improve the knowledge and creativity of the user[42-46].

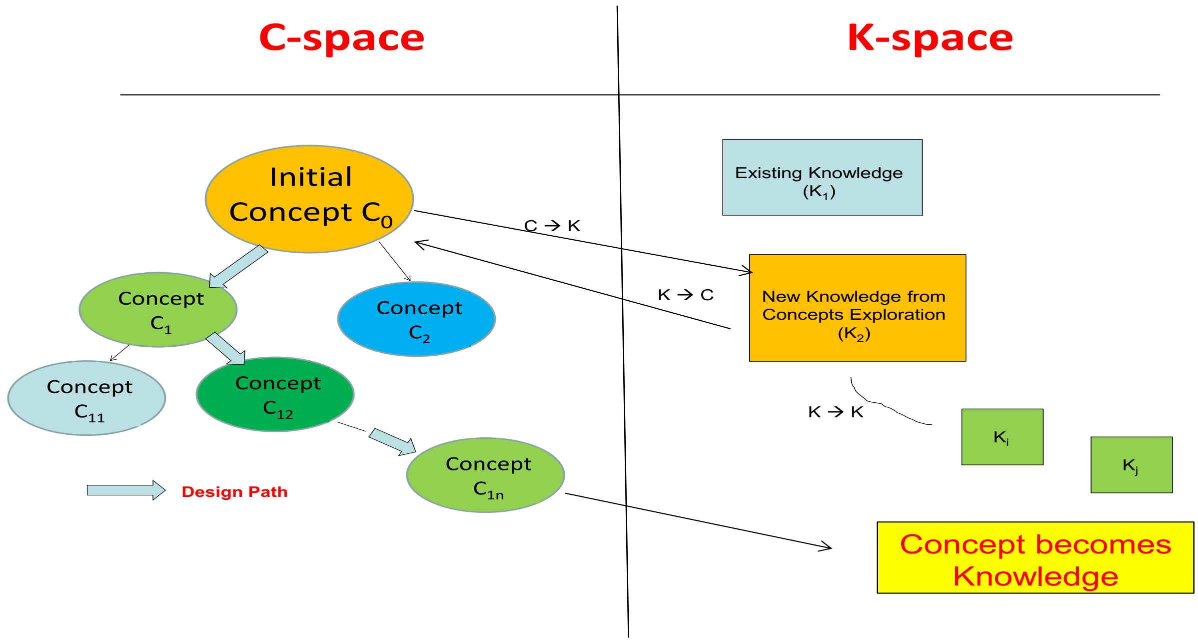

Figure 1: C-K Theory Framework (Adapted from Hatchuel and Weil 2003, 2009)

There are four operations allowed: concepts being used to generate new concepts ($C \rightarrow C$), knowledge being used to generate new knowledge ($K \rightarrow K$), conjunction or testing of a concept proposition that leads to new knowledge ($C \rightarrow K$), and disjunction or generation of a new concept from existing knowledge ($K \rightarrow C$). Concepts can only be partitioned or included, not searched or explored, in the C space. Adding new properties to a concept results in a partition of the concept into a set or into subsets. When properties are subtracted, subsets are included into the parent set. After partitioning or inclusion, concepts may still remain concepts ($C \rightarrow C$), or can lead to creation of new propositions in K ($C \rightarrow K$). Combination of knowledge or new discoveries expands the knowledge space ($K \rightarrow K$) as well as results in new concepts ($K \rightarrow C$). Innovation is the direct result of the two operations that move between the spaces: using the addition of new and existing concepts to expand knowledge, and using knowledge to expand concepts. Concept-Knowledge theory provides a framework for a designer to navigate the unknown, to build and test connections between information (i.e. analogies) by moving between the knowledge and concept spaces, and to converge on a solution grounded in theory but also new knowledge.

Design strategies inspired in part by nature provide concept space (C) as well as knowledge space (K), which provide "reinvented" or creatively adapted solutions to solve specific engineering problems. C-K theory emphasizes connection building as well as exploration and expansion of both spaces to iterate to a better solution. Knowledge is therefore not restricted to being a space of solutions, but rather it will be leveraged to improve our understanding of the innovative designs. Moreover, it requires explicit documentation of the design path, thus inherently modeling cross-domain linkages. Expansion of the C- or K-spaces leads to new paths that may be very distant from the initial unexpected property, but that will benefit from the revised traditional knowledge bases for their development. This allows designers to reorient the design process towards new directions, and, thus, new knowledge.

Utilizing C-K theory to create instructional resources that integrate biology, engineering, design, and simulation establishes a two-way connection between engineering and biology, and illustrates how knowledge transfer processes can lead to adaptive expertise. Software simulation (Figure 2) will be employed to test concepts, and the results will be used for the creation of new propositions in the knowledge space ($C \rightarrow K$). As exemplified in Fig. 2, geometry and material inspiration from nature can be used to develop models to investigate through simulations for a specific application. Guided and iterative exploration of biological systems, through CAD models and independent research, will be completed to expand and discover new knowledge applicable to design problems.

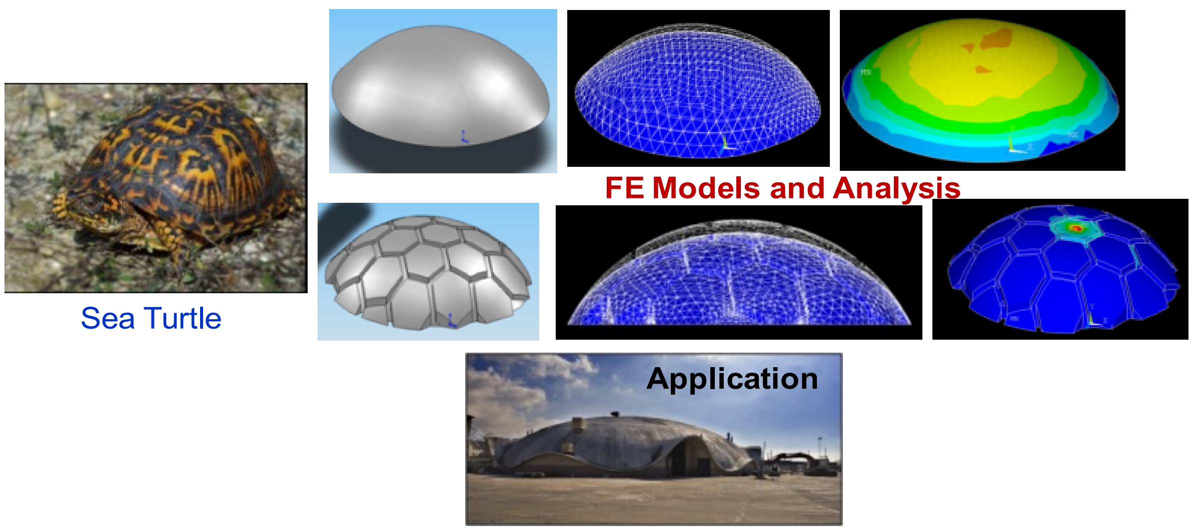

Figure 2: Examples of bio-inspired (left), design simulations (right) and application (bottom)

The instructional resources we plan to create using the C-K theory framework are outlined in Table 2. Through integration of C-K theory with instructional scaffolding, the instructional resources will accommodate diverse student learning styles and abilities.

Table 2: Summary of Planned Instructional Resources

Instructional Resource	Description
Teaching Modules	Modules will scaffold the knowledge transfer processes between domains, model adaptive expertise, model development of cross-domain linkages and utilize analogies. Modules will be in the form of lectures, case studies, vignettes and simulation-based experiments.
Learning activities	Students will engage in scaffolded, in-class exercises that promote active learning.
Assignments	Students will practice developing cross-domain linkages to and from both domains for solving engineering problems.
Design Project	Students will independently and without scaffolds apply knowledge learned in the scaffolded modules, activities, and assignments to a complex, cross-disciplinary, engineering problem.

Backwards design, a technique that starts from considering the skills and understandings that students are to learn by the end of the unit and works backward to design assessments followed by designing engaging class activities[47], will be employed to create the instructional resources. The focus is student-centered and ensures mastery through continuous feedback. Furthermore, the resources will be designed such that they can be easily integrated into existing engineering curricula. Experts in education, biology, and engineering design will assist with designing the instructional resources. We believe that using C-K theory for bio-inspired design will lead to innovative problem solving techniques (in the K space), and better solutions and enhanced learning outcomes for students (in the C space).

2.2. Accomplishing objective 2: Evaluating the learning impact of the instructional resources:

We will evaluate the learning impact of the evidence-based instructional resources from the students' perspective by measuring the effectiveness of the resources, the effectiveness of instruction, and the learning outcomes. Both formative and summative evaluation methods will be employed. Formative evaluation with emphasis on student engagement and learning outcomes will allow us to test and improve the instructional resources. Summative quantitative and qualitative analysis of data sets obtained from observations and surveys will be compared with the constant-comparative method [48].

Achievement of learning objectives will be measured using formative and summative assessment. Formative assessments will align with the designed learning activities and will scaffold on prior learning and experiences, addressing a continuum of lower level to higher level thinking and deep learning as appropriate for the curriculum. Reflection essays, class discussion, individual and group projects/products, peer review and feedback, or other types of activities will be used to measure learner progress on the learning objectives, and to provide timely and relevant feedback to both the instructor and learner. This information will be used by both the instructor and learner(s) to guide decision making and engagement in bio-inspired design. Rubrics or grading guidelines will be created for each formative assessment to ensure they align with the project goals and learning objectives.

Summative assessment will occur at the end of the bio-inspired design instruction and will be aligned to the project goals and learning objectives. Summative assessment may be individual or collaborative with peer feedback, or an individual or collaborative deconstruction and analysis of a model bio-inspired design. A rubric for the summative assessment assignment will be created, integrating the key knowledge and skills embedded in the project goals and learning objectives.

3. Research Progress

Progress toward both research objectives has been made at James Madison University with implementation plans for University of Georgia. A summary of research progress is given in Table 3. A teaching module, learning activity, assignment, and associated rubrics were created and implemented in the sophomore level engineering design course–ENGR 231: Engineering Design I[49, 50]. A C-K map template with guidelines (see Appendix A) was also created and incorporated into the learning activity and assignment. The bio-inspired design teaching module, learning activity, and assignment were integrated into the course during the second week of concept generation and introduced as a creative method to design. All assignments in ENGR 231 tie to a year-long course project of developing a human powered vehicle for a client in the community that has cerebral palsy, thus a separate project was not defined for this implementation. 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 map twice, once in class as part of the learning activity to understand the process of discovery and again in their assignment to scaffold application to the human powered vehicle.

Table 3: Research Progress Mapped to Objectives

Objectives		Progress Toward Objectives
Objective 1	Create and disseminate evidenced-based instructional resources for teaching bio-inspired design in an engineering curriculum.	
	a. Design instructional resources that facilitate identifying characteristics of engineering design problems that enable bio-inspired design.	Created sophomore level teaching module, learning activity, and assignment; planned teaching modules, learning activities, and assignments for introductory, intermediate and advanced learners
	b. Design instructional resources that facilitate the analogy mapping and transfer process of bio-inspired design.	Created C-K map template with instructions; created sophomore level teaching module, learning activity, and assignment; planned teaching modules, learning activities, assignments, and projects for introductory, intermediate and advanced learners
	c. Disseminate evidenced-based instruction-	ASEE presentation; planned journal

		al resources through publications and global educators networks.	paper submission
Objective 2		Evaluate the learning impact of the evidence-based instructional resources.	
	a.	Assess student engagement in learning.	Reflection analysis in progress for JMU; planned reflection analysis for UGA
	b.	Assess student ability to recognize and formulate interrelationships across disciplinary boundaries.	C-K Map analysis in progress for JMU; planned C-K Map analysis for UGA
	c.	Assess student ability to create bio-inspired designs.	Planned student artifact analysis for JMU and UGA

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 design, 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 ENGR 231 students in their application of bio-inspired design, two problem-driven examples using C-K theory were provided with accompanying learning activities.

The first example and learning activity focused on the hingeless facade shading mechanism, Flectofin®, inspired by the bird-of-paradise flower[41]. 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 3 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 as shown in Figure 4. The slide animations build up the information and demonstrate the four types of operators (C → K, K → C, K → K, C → C) that capture all known design properties including creative processes and explain the chaotic, iterative nature of real and practical design work starting from the C0 level and arriving at the C3 level in the concept space. Furthermore, the grey dashed arrows provide insight on how concepts are elaborated using knowledge and when the operators are used. The example concludes with explaining the technical innovation that resulted from the process of discovery.

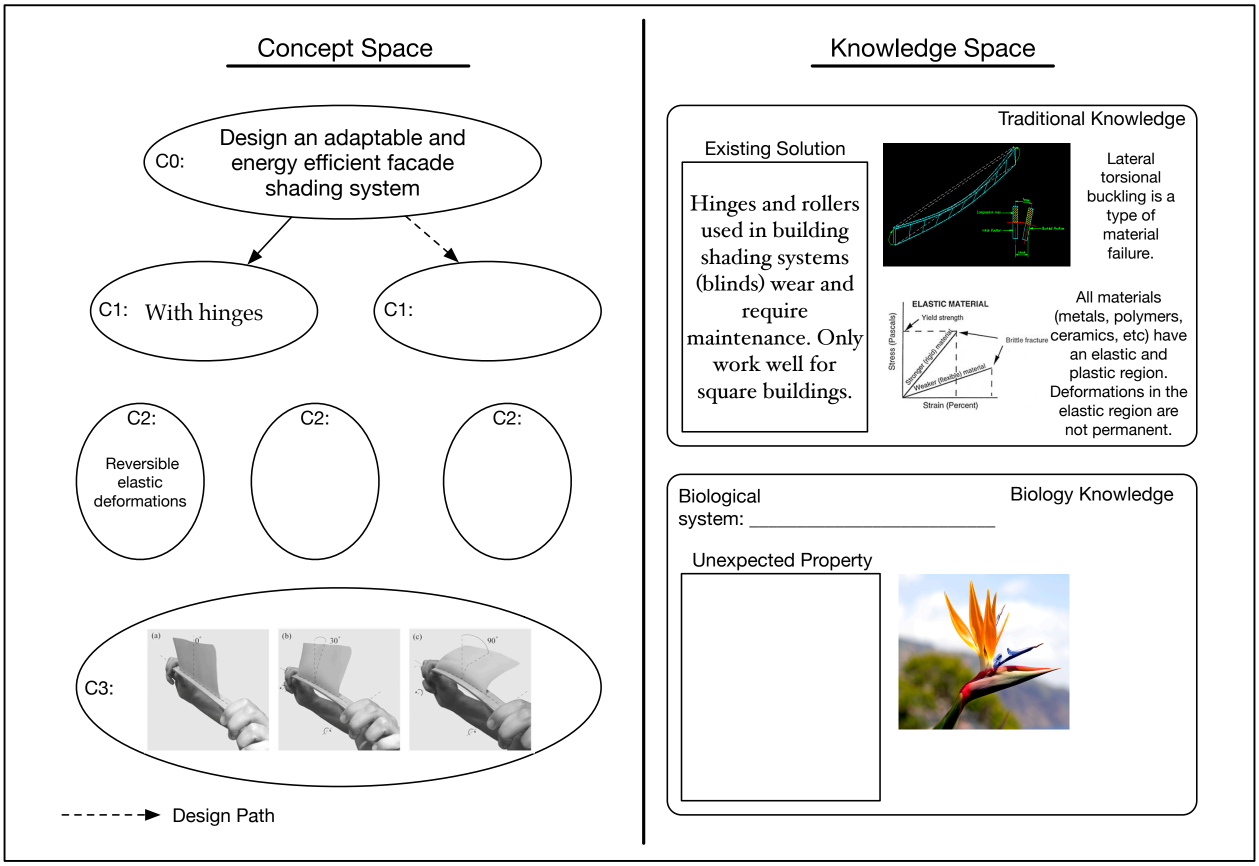

Figure 3: Template for Hingeless Facade Shading Mechanism Learning Activity

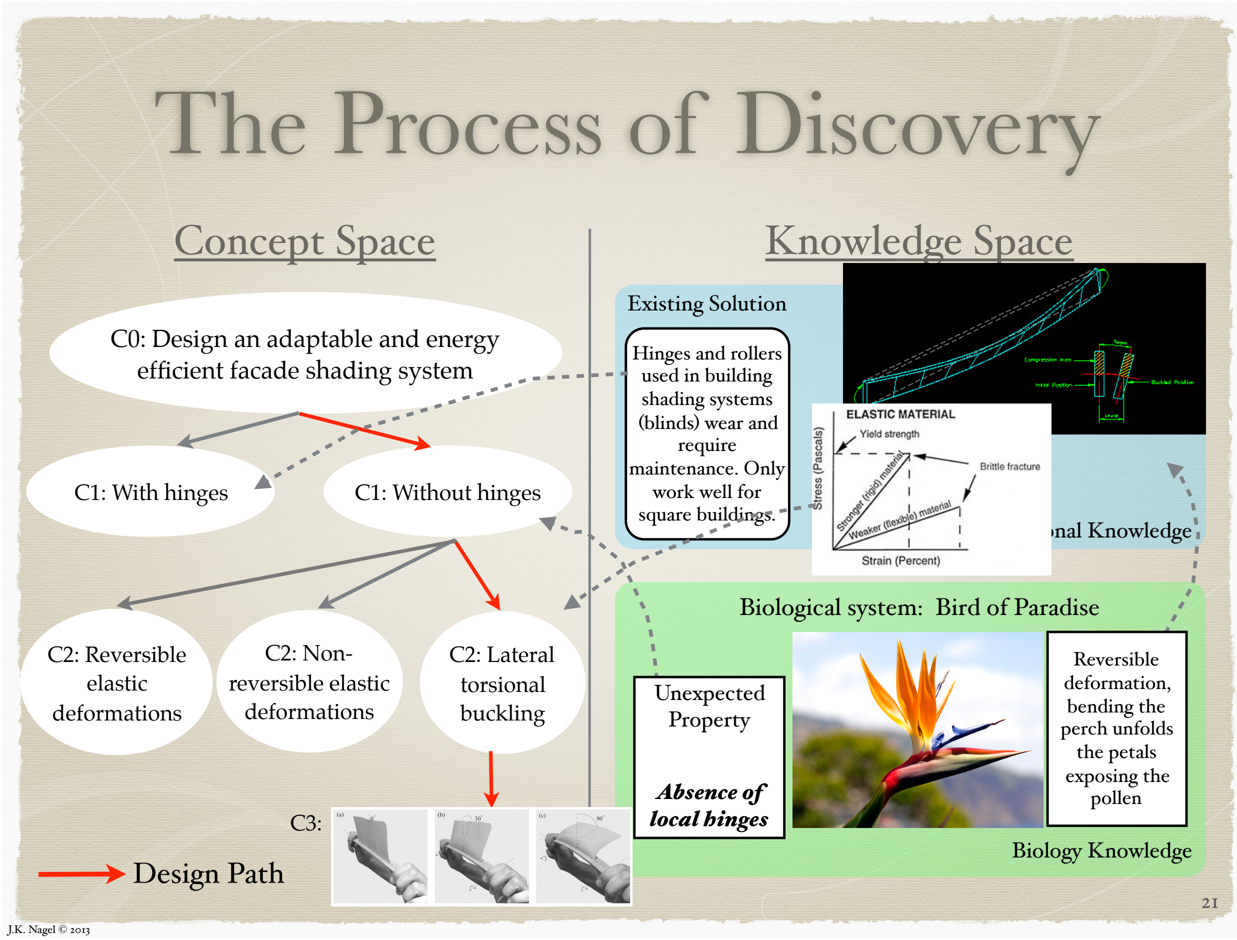

Figure 4: Slide From Teaching Module Detailing Discovery Process for Hingeless Facade Shading Mechanism

The second C-K theory example and learning activity is focused on the propulsion subsystem of a human powered vehicle. This is meant to scaffold the students in using the template, but also recognizing how the approach can be applied to their course project in a meaningful way. During this learning activity students were provided a blank copy of the C-K map template and a copy of the guidelines. Students work in small teams with more independence this time and work through each step of the guidelines while the instructor roams the room to answer questions. If several students are struggling the instructor addresses key points in the process of filling out the template with the whole class. When most teams have completed the step, the next layer of information is shown on the slide to demonstrate how an expert would go through the process, and to discuss how the connections or linkages are forming between biology and engineering. The completed slide for the example is given in Figure 5. Again, the slide animations build up the information and demonstrate the four types of operators that capture all known design properties including creative processes and explain the chaotic, iterative nature of real and practical design work.

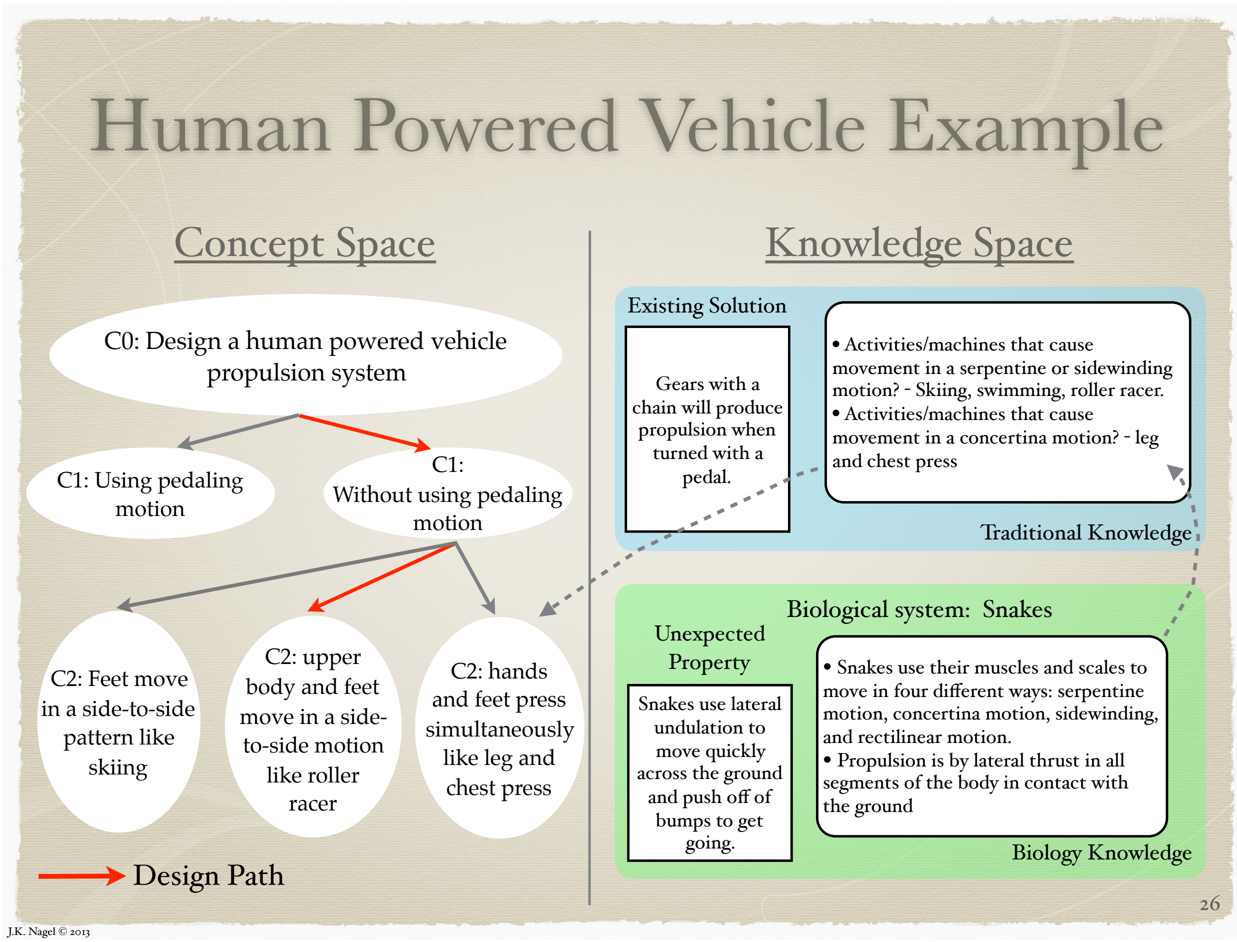

Figure 5: Slide From Teaching Module Detailing Discovery Process for Snake Inspired Propulsion System

The developed assignment that compliments the teaching module and learning activities for the ENGR 231 course includes three parts: 1) complete the C-K Map template for a human powered vehicle sub-system, 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 reflection 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. A complete sample of student work is provided in Appendix B.

The next step for this research is to address objective 2 through analysis of the student work. Analysis is currently being performed for two of the three assignment components, C-K map and reflection, with plans for analysis of the student-generated concept. Analysis of the student product (C-K map) is quantitative through the use of the rubric shown in Table 4. The rubric allows for the measure the depth and detail in the student work, as well as allows for comparison between what they did and what they said in the reflection. Additionally, the rubric allows for comparison of student work across institutions and provides an objective measure to judge transferability of instructional materials from JMU to UGA, or visa versa. Analysis of the reflection statements is through a qualitative content analysis technique to identify emergent themes in the responses to the six questions. Once themes are identified they will be compared to what was expected given the literature review and past experiences with teaching bio-inspired design.

Table 4: C-K Map Rubric

C-K Map Components	0	1	2	3
Unexpected Biological Property	Missing/ Undefined	Information is unclear, or not related to C1.	Information is moderately defined and is partially related to C1.	Information is well defined and clearly related to C1.
Existing Solution	Missing/ Undefined	Information is unclear, or not related to C1.	Information is moderately defined and is partially related to C1.	Information is well defined and clearly related to C1.
Biology Knowledge	Missing/ Undefined	Information is unclear, or not related to how C1 is achieved.	Information partially explains how C1 is achieved. Physical or non-physical attributes explored.	Information thoroughly explains how C1 is achieved. Physical and non-physical attributes explored.
Traditional Knowledge	Missing/ Undefined	Information is unclear, or not connected to the biology knowledge.	Information partially connected to the biology knowledge.	Information thoroughly connected to the biology knowledge.
Defined Dichotomy	Missing/ Undefined	Opposing language is not used. Descriptions closely match knowledge space information.	Opposing language is used but the two phrases are not opposites.	Opposing language is used and the two phrases are opposites.
Defined Rough Ideas	Missing/ No rough ideas	Some rough ideas connected to C1 and Knowledge space. Transition from knowledge space to concept space limited.	Most rough ideas connected to C1 and Knowledge space. Transition from knowledge space to concept space evident.	All rough ideas connected to C1 and Knowledge space. Transition from knowledge space to concept space strong.
Transition from Rough Idea to Sketch	Missing/ No sketches	No logical connection between C2 and C3.	Connection between C2 and C3 is logical but lacks clarity of implementation.	Connection between C2 and C3 is logical and easily envisioned implementation.
Defined Design Path	Missing/ Undefined	Convention not followed.	Defined for some levels of concept space, but not all.	Defined for all levels of concept space.
Defined Sketches	Missing/ No sketches or information provided	Information provided instead of sketches.	Some sketches of rough ideas are provided.	Sketches of rough ideas are provided.

Analysis of the student concept will be evaluated with a rubric as well to measure transferability and feasibility of ideas (i.e., coming up a concept that could be innovative rather than just looking like the biological system).

Based on reviewing the student assignments and from chatting with the students outside of class, the bio-inspired design teaching module, learning activity, and assignment were well received. Students found the topic and C-K mapping process engaging and useful. Many commented in their reflection essays that they found the technique valuable and will use it in future opportunities that require innovative solutions. Additional positive trends in the essays include students commenting that they had never considered nature as a source of design inspiration before and that this process opened up their eyes to so much potential, how impressed they were with the variety of biological systems that can inspire innovations, feelings of creativity, and that it was fun or exciting. A negative trend in the essays included feeling like bio-inspired design was not necessary for the task at hand. Detailed qualitative and quantitative analysis will confirm or disprove these observations.

Analysis on the JMU and UGA data from sophomore design courses will inform the planned teaching modules, learning activities, assignments, and projects for introductory, intermediate and advanced learners. The instructional resources will include a mix of biological phenomena that have already been exploited as inspiration for engineering solutions and others that, to our knowledge, have not yet been tapped for design potential and that we will propose as starting points for students to apply C-K theory to generate solutions for design problems of their own imagining. We want this research to be cross-cutting and applicable to a broad audience, therefore the instructional resources will be designed to facilitate identifying characteristics of engineering design problems as well as the analogy mapping and transfer process of bio-inspired design leading to new knowledge and design innovation across the following categories: system, process, function, architecture, form, material, and surface. These categories capture the wide range of design information transferred through analogies in bio-inspired design, and provide a non-discipline specific approach to organizing the information[51]. The instructional resources will be deployed to both JMU and UGA starting with the introductory resources to scaffold students in their learning of C-K theory and bio-inspired design. Then the intermediate and advanced resources will be deployed to allow students to work through increasing degrees of independent research and decision-making on their own. This approach will ensure diversity in engineering design problems and cross-disciplinary learning.

4. Research Contributions and Significance

This research directly addresses the National Science Foundation's objectives of educating students to be innovators in STEM and be scientifically literate, increasing the retention of a diverse population of STEM students, and increasing the engagement of undergraduate students in their STEM learning. We expect to produce knowledge that will improve student learning, STEM literacy, cross-disciplinary thinking, and innovation through the pedagogy of bio-inspired design in an engineering curriculum. Furthermore, 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. Using an evidence-based approach for making the creative leaps to and from the domains of biology and engineering, this work aims to meet the imperative for students to be trained in multidisciplinary design innovation to address society's future challenges. The significance of this work lies in its potential to 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.

Engineering students find bio-inspired design exciting, and it offers relevance to professional practice as well as an effective hook to frame complex, cross-disciplinary problems. Bio-inspired design is rapidly gaining in popularity in engineering courses, yet little is known about how to teach it or support students in the discovery and knowledge transfer processes that enable design innovation to occur. Concept-Knowledge theory is used to create instructional resources, as it is known for integrating multiple domains of information and facilitating innovation through connection building. 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.

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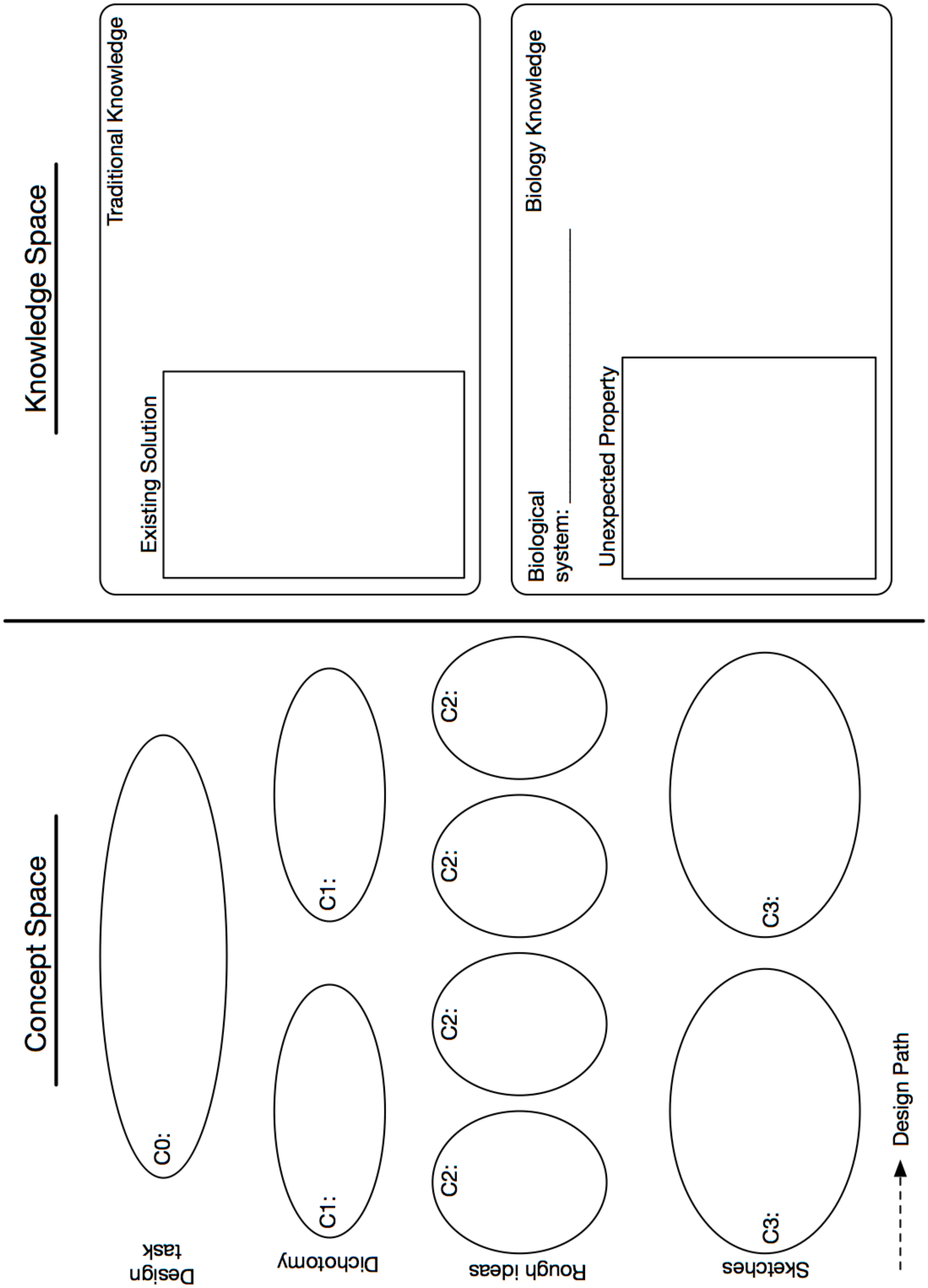
APPENDIX A



Knowledge Space
Traditional Knowledge
Existing Solution
Biology Knowledge
Biological system: ____
Unexpected Property
Concept Space
C0:
C1:
C1:
C2:
C2:
C2:
C2:
C3:
C3:
Design task
Dichotomy
Rough ideas
Sketches
Design Path

Concept-Knowledge Space Mapping Guidelines

1. Fill in the C0 bubble with a description of the design task. [K→C]
An example is: C0: Design a human powered vehicle propulsion system.

2. Ask the question, "How does nature ________________________ ? to identify a biological system that has analogous properties or characteristics. Fill in the blank with a function or description of a sub-system you are seeking inspiration for. Search a database such as www.AskNature.org to find inspiration. Put the name of the inspired biological system on the line in the Biology Knowledge box. [C→K]
Examples are: How does nature move? How does nature create locomotion/propulsion? Example biological system identified: snakes.

3. Learning from the biological system identified in step 2 and considering what you already know, create a dichotomy for the C1 bubbles. One bubble should describe how C0 is traditionally achieved, and the other bubble should describe how C0 is biologically achieved. They should be opposites. Essentially, this is a hypothesis to test. [K→C]

- Explain the C1 (traditional) in the existing solution box in the knowledge space.
- Explain the C1 (biological) in the unexpected property box in the knowledge space.

Example: C1: Using pedaling motion. (traditional) C1: Without using pedaling motion. (biological)
Example explanations: Existing solution - gears with a chain will produce propulsion when turned with a pedal. Unexpected property - snakes do not use rotational movement. They use lateral undulation to move quickly across the ground and push off of bumps to get going.

4. Dive deeper into the biological information (e.g., books, web search). How does the identified biological system achieve C1 (biological)? Consider physical and non-physical attributes. Write the information in the Biology Knowledge box. [C→K]

- Non-physical attributes - attributes the biological system performs - functions, processes, behaviors, or system characteristics.
- Physical attributes - observable attributes of the biological system - form, shape, geometry, structure, surface, patterns.

Example biological information for without using pedaling motion: snakes use their muscles and scales to move in four different ways: serpentine motion, concertina motion, sidewinding, and rectilinear motion.

5. Ask, "How does this biological information connect to what I know?" (intuitive method). If nothing comes to mind, then ask "How does this biological information connect to what is known?" (directed method) and search for information that will allow you to build connections between the biological knowledge and the traditional knowledge. Write the information in the Traditional Knowledge box. [K→K]
Example connection building thought process: snakes do not use a pedaling/rotational motion, rather then use a lateral wave motion. Propulsion is also generated by lateral thrust in all segments of the body in contact with the ground. What activities or machines move in a serpentine or sidewinding motion? - Skiing, swimming, roller racer. What activities or machines move in a concertina motion? - leg and chest press

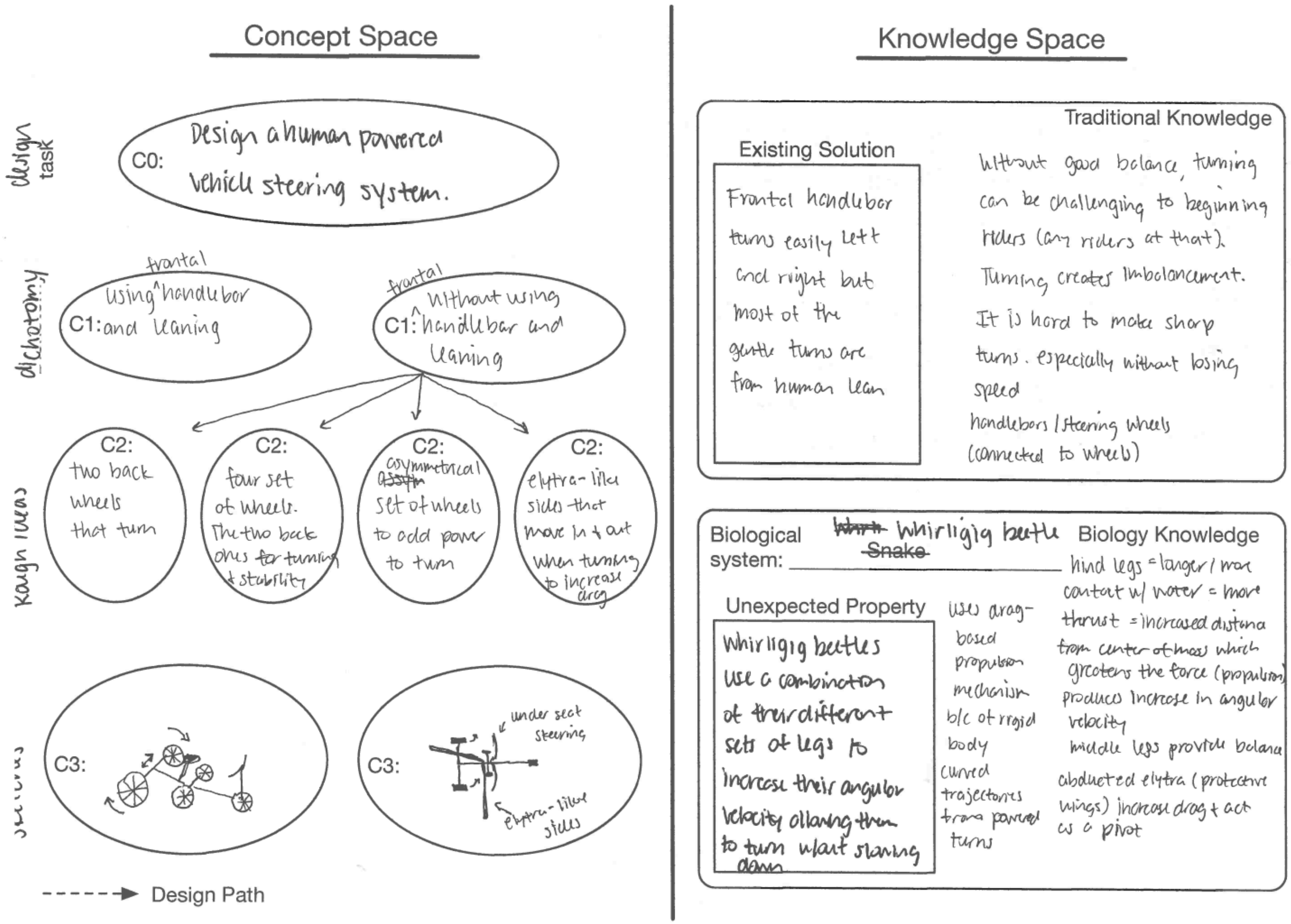
6. Turn those connections into rough ideas that could solve the design task in C0. Describe the ideas with words in the C2 bubbles. Draw arrows from the C1 bubble being expanded to C2 bubbles. [K→C]

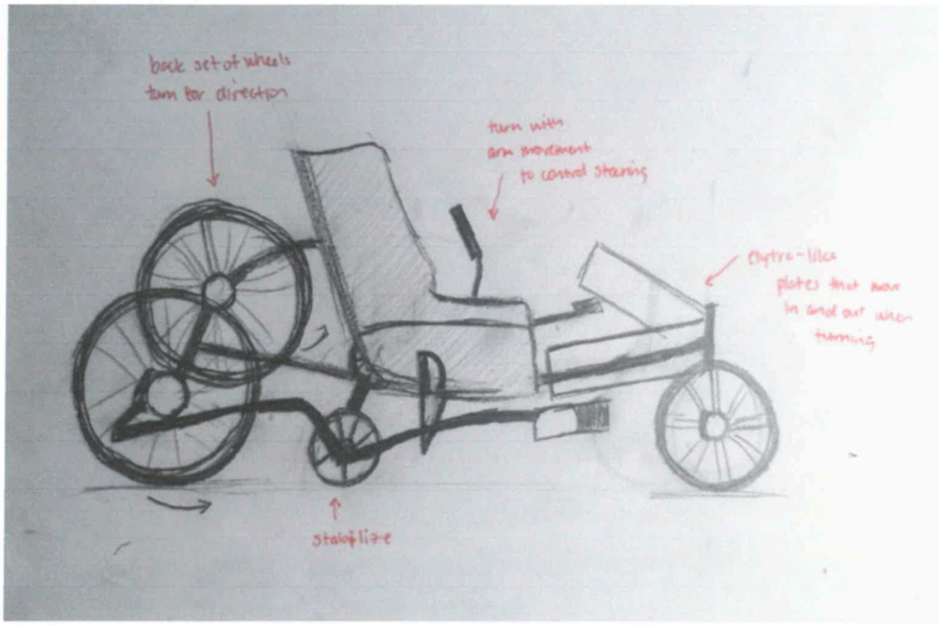
Example C2 creation: Serpentine or sidewinding motion ideas - move feet in a side-to-side pattern like skiing, upper body and feet move in a side-to-side motion like roller racer, and move upper body in a wave pattern like swimming. Concertina motion idea - hands and feet press simultaneously.

7. Expand a single C2 idea or combine C2 ideas to create a design solution(s) in C3. Sketch the solution using engineering components in the C3 bubble. [C→K]

Example C3 creation: One solution for a propulsion system could be a 4 wheeled design that requires the rider to press with alternating leg movements (a wave pattern) to propel the HPV forward mush like the roller racer.

Student J


Concept Space
Knowledge Space
design task
dichotomy
rough ideas
C0: Design a human powered vehicle steering system.
C1: using frontal handlebar and leaning
C1: without using frontal handlebar and leaning
C2: two back wheels that turn
C2: four set of wheels. The two back ones for turning + stability
C2: asymmetrical set of wheels to add power to turn
C2: elytra-like sides that move in + out when turning to increase drag
C3:
C3:
under seat steering
elytra-like sides
Design Path
Traditional Knowledge
Existing Solution
Frontal handlebar turns easily left and right but most of the gentle turns are from human lean
Without good balance, turning can be challenging to beginning riders (any riders at that).
Turning creates imbalancement.
It is hard to make sharp turns, especially without losing speed
handlebars / steering wheels (connected to wheels)
Biological system: ~~Snake~~ Whirligig beetle
Biology Knowledge
Unexpected Property
Whirligig beetles use a combination of their different sets of legs to increase their angular velocity allowing them to turn w/out slowing down
uses drag-based propulsion mechanism b/c of rigid body
curved trajectories + rapid turns
hind legs = longer / more contact w/ water = more thrust = increased distance from center of mass which greatens the force (propulsion) produces increase in angular velocity
middle legs provide balance
abducted elytra (protective wings) increase drag + act as a pivot



The pertinent subsystems that are in focus are steering and wheels.

After studying the whirligig beetle, the major takeaway from its movements is its ability to turn without slowing down. By using its hind and middle legs, the beetle keeps its angular velocity high and can turn at unbelievable angles. The above sketch is modeled after the beetle's major components to allow easier, faster, and sharper turns. The back most set of wheels will move left and right controlling the turning capabilities. The middle set of wheels will provide support much like the middle legs of the beetle. The front most wheel will be able to turn slightly to guide the bike. The turning will be controlled by under seat steering, which will be comfortable to the rider. The front plates are modeled after the beetles abducted elytra, which they use to increase drag and act as a pivot. As the human powered vehicle turns, the plates will swing out and in to contract with the wind to increase the drag. Hopefully with the back wheels being the main source of direction and the incorporation of the front plates' movement, the rider will not have to slow down when turning. The hpv will be able to turn at sharper radii with better support, allowing the rider to keep high speeds and balance. The elliptical propulsion system will connect to each set of wheels, as will the brake pads. Only the right side lever will control the braking system. The pedals will have an encasement for the rider's foot to stay secure when pedaling. The frame will hold all subsystems together.

I learned a lot about the whirligig beetle's mechanics in turning. Its ability to turn without slowing down really appealed to me, as one of Syerra's first requests is to go fast. The main takeaways from the way the beetle's body is constructed is the way it uses the back legs, that are lower on the abdomen and further from its center of mass, to do the sharp turning. Another beneficial component is its middle legs that provide balance and support. One of the biggest constraints that come with Syerra's cerebral palsy is her struggle with balance. Using the concept of having back wheels to control the direction of the human powered vehicle while also providing another extra set of wheels for support will be beneficial to her success in going fast and staying upright on her human powered vehicle.

I learned the content by first picking the subsystem that interested me most, steering. I then went on the requested website, AskNature.org to find ways nature controls the direction of the movement. The beetle stuck out to me because of the speedy turning capabilities. From this website, I researched more on the whirligig beetle by reading a more in depth article about their movements. I summed the research up by simply watching a YouTube video of how the beetle controls its motions while swimming.

With this content, I hope to implement at least one of the components I came up with inspired by the beetle. As mentioned before, I think the ability to turn at high speeds while maintaining balance would be a key component to a human powered vehicle for Syerra. Even if this does not get used, I hope it inspires someone else in my group to work toward another solution that might provide the same benefits.

I learned that this process is a fun, insightful process that helps focus solution ideas and generation. Nature is amazing and biological systems work without technological advancements. I think it is extremely important and useful to model some design elements after the way nature works because of it's success and what seems to be simplicity. Sometimes design generation gets to be too narrow focused or hard to come up with feasible options. This process allows designers to think more broadly and realistically because if nature can do it, hopefully humans can design similar success mechanisms.

I learned this process just by doing this assignment. Being introduced to the process in class helped some but after doing research, filling out the chart, and then transforming that into a drawing to explain how to implement it showed me the challenges of transforming biological systems to feasible solutions.

I am going to continue to use this process when thinking about systems and solutions. It is so interesting and exciting to see just how similar biology can be to something that you wish to create.