Teaching Bio-inspired Design Using C-K Theory

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Miss Peyton Leigh Pittman

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Introduction

The engineer of 2020 is expected to not only offer technical ingenuity but also adapt to a continuously evolving environment. The ability to operate outside the narrow limits of one discipline and be ethically grounded in solving the complex problems of the future will also be needed. To address the competencies of the future engineer, 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 train engineers in these competencies is teaching biomimicry or bio-inspired design in an engineering curriculum, which offers relevance to professional practice as well as an effective hook to frame complex, cross-disciplinary problems. This research addresses the need for undergraduate student training in multidisciplinary design innovation through the creation of instructional resources grounded in Concept-Knowledge (C-K) Theory. C-K theory is used as it is known for integrating multiple domains of information and facilitating innovation through connection building. The instructional resources include lectures, in-class activities, assignments, rubrics and templates that scaffold the discovery and knowledge transfer processes such that the natural designs can be used to inspire engineering solutions.

The instructional resources have been deployed at two predominately undergraduate institutions (PUIs) in the second-year engineering curriculum. All students were given a lecture on bio-inspired design and asked to complete the C-K mapping template in class as part of learning activities to understand the process of discovery, and again in their assignment to scaffold application to the course project. Analysis of the student-generated templates using a rubric shows that students were able to successfully use information (knowledge transfer) to make connections between biology and engineering for creating solutions for design problems. Additionally, all students were asked to respond to six reflection questions regarding the content (biology) and process (bio-inspired design). Qualitative content analysis of second-year engineering student reflection statements shows that, in both populations, the instructional resources resulted in significant learning of both biology and bio-inspired design, as well as learning engagement and value of the experience. The themes that emerged from the student responses to each reflection question correlate well with the objectives of the research. An unanticipated, but significant, result is that some students used existing biology knowledge to help understand engineered components and systems, meaning they 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.

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.

Accomplishing objective 1: Creating and disseminating instructional resources:

Salgueiredo[1] 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[2-4] 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[2-4], 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*[2-6]. 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[2-6].

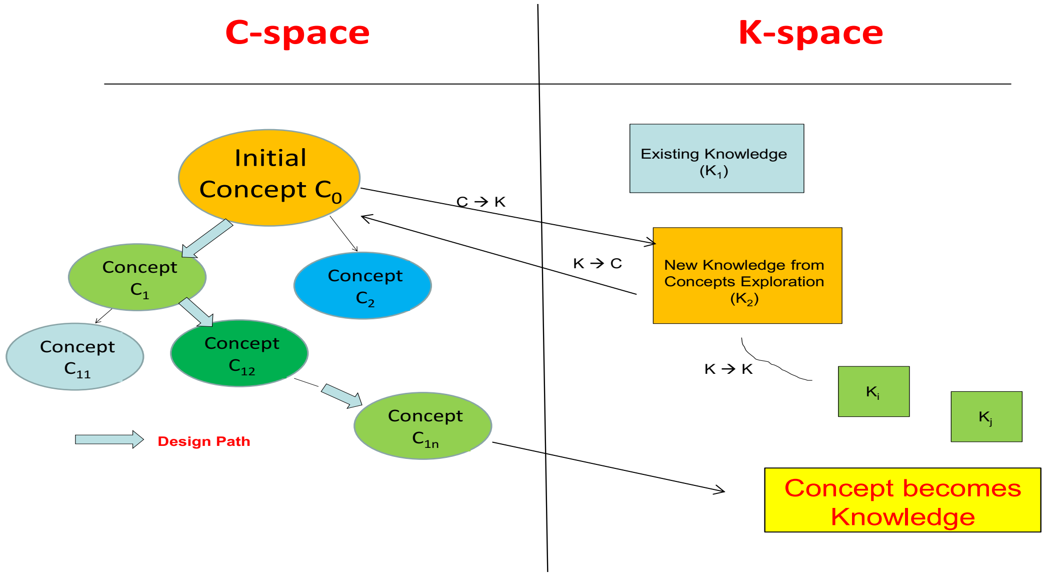

Figure 1: C-K Theory Framework

There are four operations allowed: concepts being used to generate new concepts (*C*→*C*), knowledge being used to generate new knowledge (*K*→*K*), conjunction or testing of a concept proposition that leads to new knowledge (*C*→*K)*, and disjunction or generation of a new concept from existing knowledge (*K*→*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 remain concepts (*C*→*C*) or can lead to creation of new propositions in *K* (*C*→*K*). Combination of knowledge or new discoveries expands the knowledge space (*K*→*K*) as well as results in new concepts (*K*→*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.

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[7], 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).

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. 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.

Research Progress

Progress toward both research objectives has been made at both James Madison University and University of Georgia. A summary of research progress is given in Table 3.

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; teaching modules and learning activities for interdisciplinary learning; planned learning activities, and assignments that involve software simulation
	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; teaching modules and learning activities for interdisciplinary learning; planned learning activities, and assignments that involve software simulation
	c. Disseminate evidenced-based instructional resources through publications and global educators networks.	ASEE presentation[8]; journal publication[9]; planned contribution to the Biomimicry Educators Network
Objective 2	Evaluate the learning impact of the evidence-based instructional resources.	
	a. Assess student engagement in learning.	Reflection analysis for JMU and UGA
	b. Assess student ability to recognize and formulate interrelationships across disciplinary boundaries.	C-K Map analysis for JMU; planned C-K Map analysis for UGA
	c. Assess student ability to create bio-inspired designs.	Student artifact analysis for JMU and UGA

The developed instructional resources[8] have been deployed at two predominately undergraduate institutions (PUIs) in the second-year engineering curriculum.

The instructional resources were implemented at James Madison University (JMU) in a sophomore engineering design course (23 students enrolled, consented sample size n=15) that focused on the theory, tools, and methods of the engineering design process. At the University of Georgia (UGA), the instructional resources were implemented in a sophomore design course for multiple disciplines (Agricultural Engineering, Biological Engineering and Computer Systems Engineering) (74 enrolled, consented sample size n=39) that introduced the C-K approach at the conceptual design phase. After discussing the C-K approach in both courses, a teaching module with learning activities was given, as well as an assignment related to the course project. The assignment included three parts: 1) complete the C-K mapping template for the design problem, 2) use the sketches in the template to create design concepts, and 3) a W/H/W reflection essay answering three questions about the content and process. At UGA, a quiz was given as an in-class assignment that was closed notes/book to align with the format of the course. The question UGA students answered was the following: Using C-K approach, (a) develop an innovative solution for designing a human powered vehicle propulsion system using the Concept & Knowledge space sheet. (b) Also reflect your experience of C–K approach to the following questions: What did I learn?; How did I learn it?; and What will I do with it? In addition, a senior design project focused on creating heuristic C-K cards was assigned to a group of four students at UGA. The senior students used the design process to create the heuristic C-K cards with the goal of introducing these cards in the conceptual design phase of the sophomore design course. Assessment of student work was completed using a C-K map template rubric (Table 1) and qualitative content analysis[10] that identified themes in student reflection statements. The results section provides comparative data for the student reflection statements.

Table 4: Rubric for Scoring C-K Map Templates

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 provided	Information provided instead of sketches.	Some sketches of rough ideas are provided.	Sketches of rough ideas are provided.

Results and Discussion

Students at JMU and UGA completed the C-K mapping template three times: twice in class as part of learning activities to understand the process of discovery and again in their assignment to scaffold application to the course project. An example student C-K map and resultant concept sketch is given in Fig. 2.

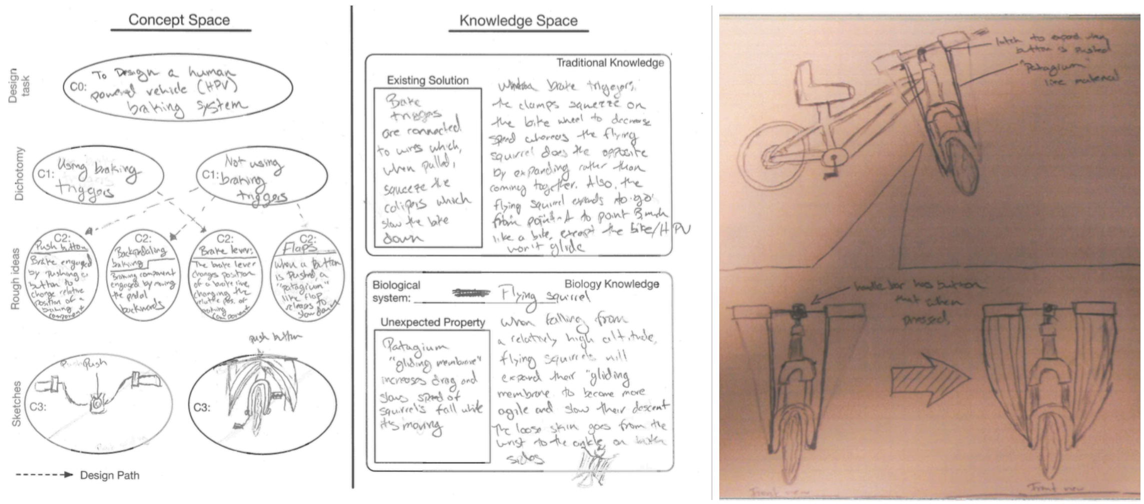

Fig. 2: Example of JMU Student C-K Map and Human Powered Vehicle Concept

Both JMU and UGA datasets were analyzed using qualitative content analysis, and the JMU dataset was also analyzed quantitatively using rubric scoring. The compiled rubric scores for JMU student templates (n=15) are given in Table 2. Scores at or above 18 indicate that students understood the template and process. Analysis of the JMU student-generated templates using the rubric (Table 1) shows that students were able to successfully use information (knowledge transfer) to make connections between biology and engineering for creating solutions for design problems.

Table 5: Rubric Scores for C-K Map Templates

Student A	18	Student I	21
Student B	20	Student J	25
Student C	22	Student K	23
Student D	14	Student L	17
Student E	18	Student M	22
Student F	21	Student N	21
Student G	21	Student O	20
Student H	16		

Table 3, which is the scored rubric for the template generated by Student F (Figure 2), gives an example of how the sums of each student were computed for Table 2. There are nine different components of the rubric, each with a possibility of 0 to 3 scoring. For an overall sense of the different scores that could be obtained from the rubric, a score of zero would indicate that none of the C-K map was filled out or that every part of it was not clearly defined. A score of 27 would indicate that the student's C-K map was filled out completely, and every level flowed together and was well defined such that almost anyone could follow the process and understand how the map was completed.

Table 3: Scored Rubric for Student F's C-K Map Template

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 provided	Information provided instead of sketches.	Some sketches of rough ideas are provided.	Sketches of rough ideas are provided.

For student F specifically, s/he scored a 3 for Unexpected Biological Property because a clear statement about the flying squirrel's method of slowing down directly links to the C1 dichotomy (using or not using braking triggers) and contrasts the existing solution. The student also scored a 3 for the Existing Solution component because there was an undoubted connection to the biology portion of the map, and it transferred directly to the C1 dichotomy. Biology Knowledge was scored as a 2 because although the student explained the physical attributes associated with the biological property, s/he failed to explore the non-physical attributes. Threes were scored for both Traditional Knowledge and Defined Dichotomy. The Traditional Knowledge explicitly links back to the Biology Knowledge which shows further understanding of the process. The C1 dichotomy contained exactly opposite phrases. The student scored low for Defined Rough Ideas because not all of the ideas were related to the negative dichotomy. There was also little indication that these ideas were derived from the unexpected biological property. Transition from Rough Ideas to Sketch scored a 2 because it was obvious that the sketch came from the rough ideas, but two of the defined ideas were combined. This combination of ideas negatively impacted the clarity of implementation. The Defined Design Path scored a 2 because arrows were drawn only from C1 to C2 so the full understanding of the choices made was incomplete.

Finally, Defined Sketches scored a 2 because only one rough idea was sketched out and a clear linkage of C2 to the sketches was missing.

Tables 4 and 5 show the results of qualitative analyses, in which the coded meaningful units of information from the student responses to each reflection question were grouped into categories and themes (T1-4; parentheses show the number of units in each category or theme). Categories in red text are from UGA student responses, those in purple are from JMU student responses, and those in black are from both groups. Comparing Tables 4 and 5 by type of question reveals a positive effect of the C-K theory-based instructional resources. Student responses to what was learned about process indicated that some students recognized the value of using existing biology knowledge to help understand engineered components and systems. This emergent trend was unexpected and points toward the significance of teaching bio-inspired design in an engineering curriculum.

Table 4: Themes and Frequency for Content Reflection Questions

What did I learn about the content?	How did I learn the content?	What am I going to do with the content?
T1: Valued what can be learned from nature and biology (31) – Nature has surprisingly complex systems that work well especially since they have been around for years (11) – Nature has a lot to offer for potential solutions (15) – Nature has attributes that can easily be iterated into design (5)	T1: Course learning resources (50) – Class examples (1) – Filling out C-K mapping template (3) – Class lectures (28) – Reading book (6) – Applying it to class project (12)	T1: Facilitate a future design path (45) – Apply to future problems or projects (30) – Gain new perspective when designing (6) – Apply it to real world problems and every day life (5) – Unsure of future use (3) – Put it on a C-K map (1)
T2: In-depth understanding of chosen biological system (14) – Detailed biological information on specific topic (12) – Gained knowledge about biological subsystems (3)	T2: Scholarly or external resources (40) – Further exploration or analysis of information (29) – Independent research using websites provided (9) – Previous knowledge (2)	T2: Apply to immediate problem (25) – Apply to class assignment – Human Powered Vehicle (12) – Apply to class project (9) – Maybe apply it to class (HPV) but question necessity or feasibility (4)
T3: Cross-domain linkages (34) – Formed a connection between HPV design and chosen biological subsystem (10) – Gained further knowledge about specific subsystem of HPV (1) – Understood connection between concept and knowledge (10) – Learned about the C-K mapping and how to do the process in general (13)	T3: Study and practice (11) – Practicing the process (6) – Studying for a quiz (5)	
T4: Biology is not always applicable (8) – Biology does not relate to class assignment (3) – Nothing (1) – It is confusing (1) – Non bio-inspired design tools (3)		

Table 5: Themes and Frequency for Process Reflection Questions

What did I learn about the process?	How did I learn the process?	What am I going to do with the process?
T1: Recognized knowledge transfer between domains for problem solving is possible (30) – Biology can inspire solutions to problems (11) – How to apply C-K Theory to bio-inspired design (10) – More biological analysis is needed than anticipated (7) – Facilitates connecting an engineering sub-system to a biological system (2)	T1: Course learning resources (58) – Using the C-K mapping template (11) – Through lecture and in-class activities (28) – Application to course project (11) – Studying for quiz (5) – Reading textbook (2) – Transforming the template information into a drawing (1)	T1: Facilitate a future design path (20) – Use it when designing or problem solving in the future (31) – Use method to expand design space (6) – Use in career (3) – Use for class project (7) – Add to engineering toolbox (4) – Use existing biology knowledge to help understand engineered components and systems (3) – Use in all aspects of life (2)
T2: Valued the inclusion of biology in engineering design (40) – Keeps the design space open to more ideas (30) – Bio-inspired design is a process similar to the engineering design process (10)	T2: External resources or practice (25) – Previous knowledge (5) – Independent research (9) – Independent practice (8) – Applying an engineering problem solving approach (2) – Existing bio-inspired designs (1)	T2: Apply to immediate problem – class project (3) – Use for class assignment – Human Powered Vehicle (2) – Continue research (1)
T3: Bio-inspired design is not always applicable (10) – Sometimes bio-inspired design is not feasible (2) – It is time consuming (5) – It is not easy (2) – Nothing new (1)		T3: Reluctant to use in future (3) – Uncertain about future use (2) – Not sure (1)

The number of shared responses found in the themes reveals another positive effect of the C-K theory-based instructional resources because it shows that useful knowledge was gained through similar processes. Students at both institutions found the topic and C-K mapping approach engaging, useful, and inspiring that it is used in industry for the creation of innovative designs. Many commented in their reflection essays that they found the C-K mapping approach valuable and as a tool to add to their engineering toolbox. Additional positive trends in the essays include: students had never considered nature as a source of design inspiration before and were impressed with the variety of biological systems that can inspire innovations, students clearly recognized the cross-domain connections between engineering and biology through the C-K mapping approach, students had feelings of creativity during the process, and students found bio-inspired design fun or exciting. A negative trend in the essays included feeling like bio-inspired design was not necessary for the task at hand or was confusing.

The main differences between JMU and UGA themes emerge from the differences in the curriculum, i.e. the different projects that each institution applied the process to. Highly supported themes that related to learning the content specific to UGA revealed that the students had an additional quiz to complete that helped them practice the process in a timed manner. Other themes indicated that UGA students strongly understood the connection between the knowledge and concept sides of the C-K map which indicates strong success in the process itself. One highly supported theme, specific to UGA, related to learning the process indicated that the students understood that the C-K theory is just one way to apply biology to the engineering design process. There was a clear connection between the usefulness of the C-K process when looking to apply bio-inspired design. UGA theme responses also indicated that the students valued using the content and process learned in class and recognized the value in future applications or in their careers.

The JMU data differed from the UGA data in showing that students gained an appreciation for applying attributes of nature to an engineering design. The students' responses revealed that they gained significant knowledge about biological systems in general. This is another positive effect of the C-K theory-based instructional resources as engineering students are not required to take any biology courses throughout their undergraduate education. JMU students heavily linked the process specifically to their semester long project of designing and building a human powered vehicle. Although all JMU students applied the process to the same project, many commented on the usefulness of using bio-inspired design in future applications that required innovation or creative ideas. There was clear understanding that bio-inspired design is another way to perform concept generation during the design process which lead to some students reporting that this specific process was useless for the course project. Overall, JMU students revealed that in-class examples and filling out the C-K map was beneficial in learning the process.

Conclusion and Future Work

Based on the assessment results from student reflection responses and the student work products, these students demonstrated engagement in learning, an ability to recognize and formulate interrelationships across disciplinary boundaries, as well as bring innovation to the design solutions. The student responses from the reflection questions and consideration of what the instructional resources were intended to foster led to the creation of a map of competencies for the 21st century engineer that can be attained by teaching bio-inspired design to engineering students[11].

The student responses indicate that bio-inspired design fosters the following competencies of the 21st century engineer: holistic, critical thinking; creativity; self-regulated learning; and complex, multidisciplinary problem solving. Exposing students to the abundance of design examples that can be found in nature and scaffolding the discovery and knowledge transfer process such that those natural designs help inspire engineering solutions resulted in significant learning of both biology and bio-inspired design, as well as learning engagement and value of the experience.

Progress has been made toward the research objectives. Future work will focus on the development and refinement of instructional resources as well as conducting design studies to demonstrate the effectiveness the C-K theory based approach. Controlled experiments to test the C-K theory based approach against another bio-inspired design method, such as the design spiral created by the Biomimicry institute, will be conducted.

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