Preliminary Findings From a Comparative Study of Two Bio-inspired Design Methods in a Second-year Engineering Curriculum

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Abstract

The engineer of 2020 is expected to not only offer technical ingenuity but also adapt to a continuously evolving environment while being able to operate outside the narrow limits of one discipline and be ethically grounded in solving the complex problems of the future. To build 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.

Our research addresses the gap in resources for effectively teaching engineering students how to perform bio-inspired design by creating instructional resources based on Concept-Knowledge (C-K) design theory. C-K theory is known for integrating multiple domains of information and facilitating innovation through connection building. We used this theory to create lectures, in-class activities, assignments, rubrics and templates that scaffold the discovery and knowledge transfer processes involved in using natural designs to inspire engineering solutions.

To assess the learning impact of our C-K theory instructional resources, we conducted a statistical comparison of student projects produced in a second-year engineering class exercise using instructional resources from C-K design theory and from the popular Biomimicry Institute (BI) design lens approach. A total of 105 students consented to participate; 2 course sections (N=51) used the C-K approach and 3 course sections (N=54) used the BI approach. Scores assigned to the students' concepts were used to test whether the C-K approach resulted in higher quality design concepts. The sections using the C-K approach were found to generate concepts that more closely resembled biological inspiration, meaning that they demonstrated innovating from nature rather than simply copying from nature. They were also more successful in abstracting biological system principles to create high quality concepts. Sections using the BI approach generated concepts that more closely resembled biological imitation, meaning that they tended to fixate on observable features and produced concepts that look or act exactly like the biological systems. These findings provide conclusive evidence of learning impact and support design theory based bio-inspired design pedagogy.

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]. Furthermore, with greater emphasis being placed on understanding the social, economic and environmental impacts of engineered solutions, another essential competency is the cognitive flexibility to think about the whole system at different levels of fidelity and in different time scales [3, 4]. 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 an engineering curriculum [5]. 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 [6].

Incorporating all STEM disciplines 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 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 [7, 8]. 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 [9, 10]. Having to retrieve and transfer knowledge from domains outside of engineering forces students to adapt to unfamiliar languages and content formats (which addresses non-technical skills) in order to apply the biological information intelligently to engineering problems (which addresses technical skills). Additionally, biomimicry 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.

Showing engineering students the significance and utility of bio-inspired design is easy. Teaching them how to do bio-inspired design without also requiring them to be fully trained as biologists is much more difficult. Teaching bio-inspired design in an engineering curriculum relies 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. 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 repeatedly cited as the major challenges with teaching bio-inspired design to engineers [11-19]. This is an important gap to address since effective navigation between the engineering design and biology spaces builds connections that facilitate innovative design and increase engineering students' cognitive flexibility, creativity, and adaptive problem solving skills [20]. The research presented in this paper aims to address this gap through developing effective instructional resources grounded in C-K Theory that will

assist engineering students in transferring knowledge between the domains of engineering and biology.

2. Background

This section reviews current efforts to incorporate biomimicry in engineering curricula, as well as the two teaching approaches compared in this study: C-K approach and the BI approach.

2.1 Current Status of Bio-inspired Design in Engineering Programs

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 [7, 8, 11, 14-16, 18-27]. 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.

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 [28-30]. 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 [29]. 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 [31]. 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 [14]. 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 [25]. 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 [23]. 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 [19]. Students study biological locomotion and how it can inspire efficient mechanisms of motion.

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. These 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 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 a general lack of engineering-focused, evidence-based instructional resources available to faculty that wish to integrate bio-inspired design into their courses.

2.2 C-K Theory

C-K theory, introduced by Hatchuel and Weil [32-34], integrates creative thinking and innovation by utilizing two spaces (Fig. 1): (1) The knowledge space (K) – a space containing propositions that have a logical status (i.e., are determined); and (2) The concepts space (C) – a space containing concepts that are propositions that have no logical status (i.e., are undetermined) in the *K* space [32-36]. This means that when a concept is formulated, it is impossible to prove that it is a proposition in the *K* space. Rather, concepts generate questions and research to answer those questions will generate new knowledge that will provide new attributes for new concepts. The wider the initial knowledge space 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 the cognitive processes of generating concepts from existing concepts and transforming concepts 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 [32-36].

There are four operations allowed: expansion of each space ($C{\rightarrow}C$, $K{\rightarrow}K$), conjunction which is testing a concept proposition to lead to new knowledge ($C{\rightarrow}K$), and disjunction which is a new concept being generated from existing knowledge ($K{\rightarrow}C$). Concepts can be partitioned or included, but not searched or explored in the C space. Adding new properties to a concept results in the concept being partitioned into sets or subsets of concepts. The reverse, subtracting properties from a concept, results in subsets being included in the parent set. After partitioning or inclusion, concepts still remain as concepts ($C{\rightarrow}C$), but they can also lead to the creation of new propositions in the K space ($C{\rightarrow}K$). The combination of different pieces of knowledge and the addition of new discoveries expand the K space ($K{\rightarrow}K$) and can result in new concepts ($K{\rightarrow}C$). Innovation is the direct result of the two operations that move between the spaces by using the addition of new and existing concepts to expand knowledge, and using knowledge to expand concepts. C-K theory thus provides a framework for a designer to navigate the unknown, to build and test connections between the K and C spaces, and to converge on a solution grounded in theory combined with new knowledge.
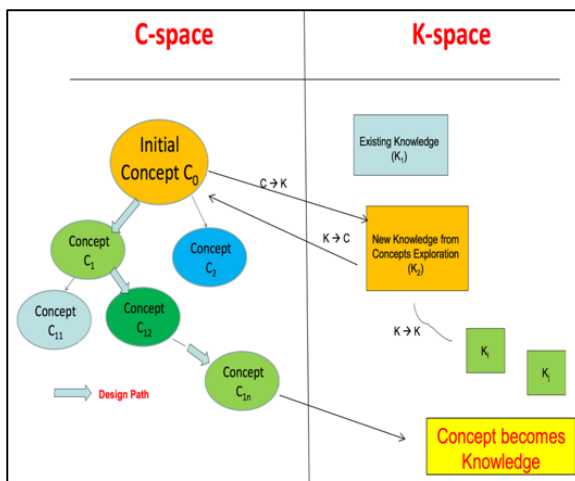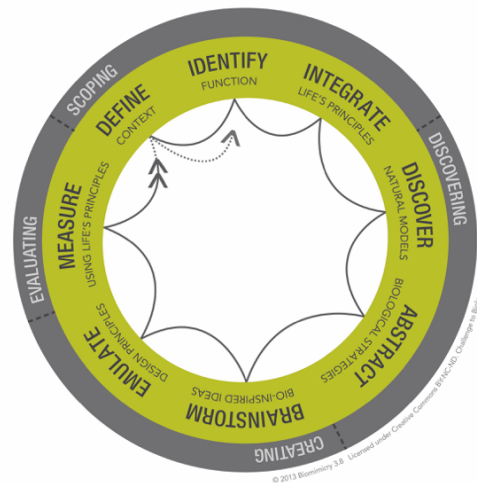

Figure 1: Concept-Knowledge Theory Framework

Figure 2: Biomimicry Institute Design Lens

2.3 Biomimicry Institute Approach

A popular approach to bio-inspired design is the Biomimicry Design Lens (Fig. 2) created by the Biomimicry Institute. Its popularity is attributed to its accessibility via the Biomimicry Institute's website and to its approach not being limited to a specific type of problem or practitioner (e.g., biologist, engineer). This approach is coupled with the AskNature.org website, which is a public database of biological information organized by a biomimicry taxonomy [37].

The cognitive process of this approach is divided into the steps of scoping, discovering, creating, and evaluating (Fig. 2), and is structured around the search for particular biological insights to

solve a given problem. Scoping involves specifying the problem to be solved with operating conditions, the functions that must be performed, and which life's principles the design will incorporate. Discovering involves identifying biological systems that have evolved strategies to solve the defined function(s) followed by abstracting those strategies into possible design principles. This step is often guided by the question, "How would nature tackle or accomplish the same problem?" Creating involves brainstorming ideas for how to apply the abstracted design principles followed by generating concepts that take into consideration aspects of scale, form, process and ecosystem. The final step of evaluating entails using life's principles as an assessment checklist. As shown by the arrows on the inside of the circle, the process is meant to be iterative to improve the outcome.

3. Using C-K theory for Designing Instructional Resources

This section reviews how and why the C-K approach should be utilized to generate instructional resources that integrate biology, engineering, and design theory to establish a two-way connection between engineering and biology, and scaffold the process of discovery for novice engineering designers. As shown in Fig. 3, the cognitive steps involved in bio-inspired design are generally similar to the early phases of the traditional engineering design process. Using a problem-driven approach, meaning the bio-inspired design process starts with a given problem, the problem is first understood and defined. To assist with translating the problem into a context amenable to bio-inspired design, the problem is reframed through abstraction. This generalizes the problem to broaden the inputs for the search task. The third step is to identify biological inspiration sources using a search technique or database. Once a set of inspiring biological organisms or phenomena are identified, they can be studied further to facilitate knowledge transfer. Analysis of biological principles or strategies leads to a deeper understanding of the inspiration sources which can then result in abstractions for analogy mapping. The final step is to generate concepts and select those that can be moved forward to the embodiment phase of the traditional engineering design process. It is in the feedback loop of transfer and apply– investigating a biological inspiration source and applying the learned knowledge by generating new concepts–that the discovery of innovative bio-inspired solutions occurs. During the discovery part of the process, knowledge and concepts are being both used and exchanged in much the same way as the C-K design theory predicts. C-K theory further presents a theoretical basis for formalizing instructional resources that will more effectively bridge the knowledge gap between engineering and biology, and facilitate the discovery of biomimetic innovations.
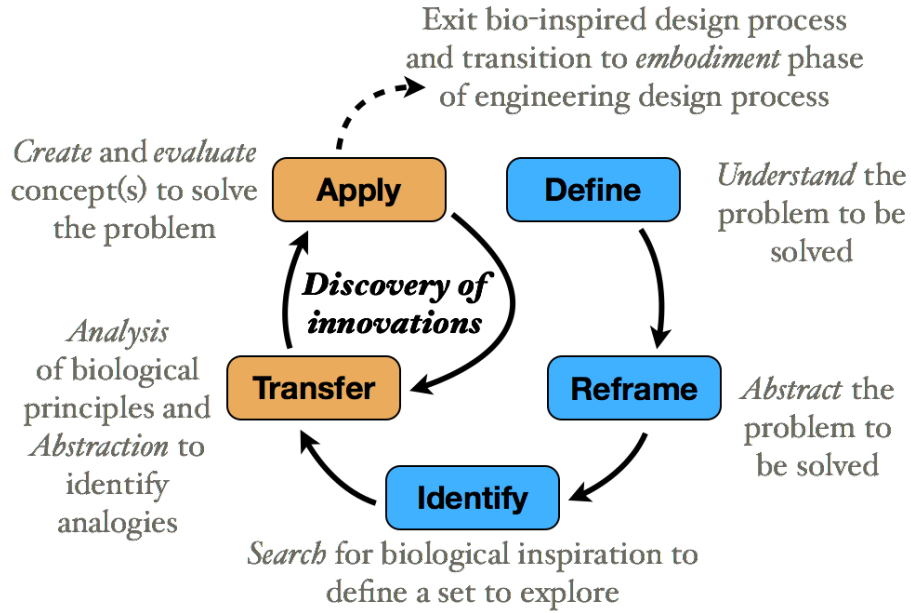
Figure 3: Bio-inspired Design Process

This approach is predicted to offer many benefits. C-K theory is adaptive and generalizable across scientific domains, which makes it applicable to a wide range of engineering problems (i.e., electrical, mechanical, material, chemical). C-K theory also emphasizes connection building through exploration and expansion of the *C* and *K* spaces to iterate to a better solution. Knowledge is therefore not restricted to being a solution space, but rather is leveraged to improve understanding of the innovative designs. Furthermore, C-K theory requires explicit documentation of the design path, thus inherently modeling cross-domain linkages. Table 1 summarizes the characteristics of the C and K spaces that facilitate the discovery of bio-inspired innovations.

Table 1: Characteristics of the concept and knowledge spaces that support the knowledge transfer needs of bio-inspired design
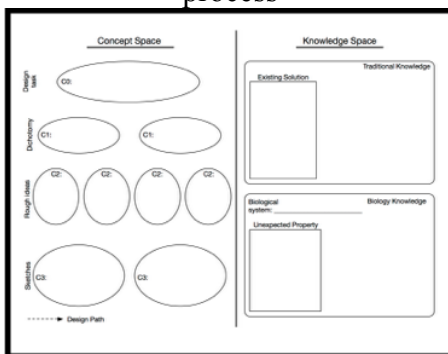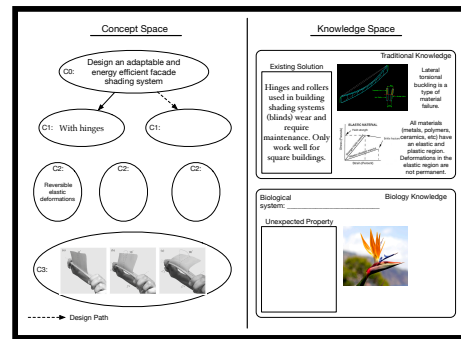
Concept Space	Knowledge Space
Posing questions to explore/answer	Analysis of existing knowledge (digging deeper)
Creation and partitioning of ideas	Drawing connections/linkages across knowledge
Documentation of a design path	Recognizing unexpected properties (opportunities)
Supports a problem-driven approach	Supports a biology-driven approach

Knowledge transfer from biology to engineering is recognized in the literature as a persistent challenge for bio-inspired design [38, 39]. Specifically, the understanding and evaluation of biological models, the abstraction of biological principles or strategies, and analogy mapping all need to be addressed to make bio-inspired design a widely adopted process. Salgueiredo [40, 41]

first proposed applying C-K theory to bio-inspired design, and provided a starting point for developing our C-K theory based instructional resources shown in Figure 4 [42, 43].

Teaching Module: exposure to breadth of inspiration and innovation and models the process

Learning Activities: In-class exercises that promote active learning and development of cross-domain linkages

C-K Mapping Template: visually structures the knowledge transfer process

Assignment: practice developing cross-domain linkages and reflection

Figure 4: C-K Theory-based Instructional Resources

4. Background for the Comparative Study

Our comparative study to test whether the C-K theory instructional approach improves the quality of bio-inspired design concepts was carried out on second-year engineering students in an engineering design course at James Madison University. These students are in the first semester of the engineering design sequence of the curriculum and are learning the engineering design process while applying the tools and methods to a course project. A total of 105 students in five sections of the course consented to participate in the study. 51 students across 2 sections were instructed to use the C-K approach and 54 students across 3 sections the BI approach. All students first received a lecture on bio-inspired design in a single 100 minute class period. The lecture had three parts: (1) design by analogy, (2) fundamentals of bio-inspired design with key examples, and (3) presentation of one of the two instructional approaches with in-class learning activities. Each student was then asked to complete an assignment using the instructional approach they had been taught, and submit it the following week.

The lecture began with the fundamentals and key examples of bio-inspired design, starting with analogy. For our purposes, analogy means using similarities between two entities that are otherwise dissimilar for the purpose of explanation or clarification. Students are presumed to have enough familiarity with one of the entities that its comparison with the other helps to draw connections to the latter. For example, electrons rotating around the nucleus (a high school- or university-level cognitive challenge) can be compared with planets rotating around the Earth, which is a middle school concept and one that most students are comfortable with by university age. Students started thinking about analogies by doing an in-class exercise of developing a concept for an exercise device that could be carried in a suitcase. This required considering both physical and non-physical characteristics like function, structure, form, surface, materials, process, and system.

The lecture moved on to knowledge transfer by comparing analogies to problem solving, and learning how analogies can strengthen solutions for the task at hand. Examples include comparing a human's blood clot to a traffic jam when looking at the whole map of the United States. This is meant to demonstrate how biological systems can be linked to engineered systems. The lecture then explained what bio-inspired design is and is not, and the two design paths of problem-driven and biology-driven; the final part of the lecture with in-class learning activities was explicitly on the problem-driven approach.

The remainder of the lecture focused on either the C-K approach or the BI approach. Each approach was demonstrated by two in-class learning activities. The first involved a detailed account of how to apply the approach using an example from the literature (Flectofin hingeless louver system for C-K, Entropy carpet tiles for BI), and students were expected to follow along with the respective bio-inspired design template provided. The second activity focused on the propulsion subsystem of a human powered vehicle (course project design problem) and was less structured to allow students to work together in small groups to complete the activity, with the instructor showing example solutions for each step of the method as students completed them. The second learning activity topic and solution were the same for both approaches.

Following the lecture, students in both groups were given an assignment involving four tasks: (1) creating a propulsion sub-system concept for a human powered vehicle based on inspiration from the Northern Leopard Frog using the instructional approach they had been exposed to; (2) creating a concept for any human powered vehicle sub-system (e.g., steering, structure, seating, braking) using a biological system of choice using instructional approach they had been exposed to; (3) creating a full system concept using one or both of the biologically inspired sub-systems from tasks 1 and 2 and the team's morphological matrix; and (4) completing reflection questions about bio-inspired design. The C-K approach sections were given the C-K theory mapping template (Figure 4) with guidelines that encouraged students to dive deeper into biological information and to consider different attributes of the biological system. The BI sections were shown how the process is split into 4 categories: scoping, discovering, creating, and evaluating, with emphasis that the process is iterative. Both groups were shown AskNature.org as a resource for finding inspiration and learning about biological systems. Overall, students incorporated the

bio-inspired concepts into their human powered vehicle designs to create new concepts for their final human powered vehicle. The comparative study is performed on the output of tasks 1 and 4.

5. Analysis, Results and Discussion

In this section, the analysis and results of the data collected during the comparative study are presented. The section concludes with a discussion of the results.

5.1 Task 1 - Creating a single propulsion sub-system concept

Both groups were tasked with creating a single propulsion sub-system concept for a human powered vehicle based on inspiration from the Northern Leopard Frog. The output from this task for the C-K group was a completed C-K map, and for the BI group a response to each of the eight steps of the Biomimicry Institute approach. Incomplete assignments were removed prior to the analysis. Concept quality was analyzed in two ways: (1) qualitative affinity sorting to identify trends and (2) statistical analysis of concept scores.

Two themes of biological inspiration and engineering implementation were chosen for affinity sorting because prior studies have shown that bio-inspired design often leads to concepts that imitate the biological system appearance but are not necessarily sensible for the problem [17, 39]. High quality concepts are judged to use biological principle information as inspiration for design and to make connections to engineering principles. Lower quality concepts are judged to closely mimic the observable aspects (e.g., physical attributes, movements) of a biological system and to present less practical engineering solutions.

Biological inspiration data was determined from the biological knowledge box of the C-K map and the abstract step of the BI design lens. Biological imitation is defined as directly copying observable aspects of the biological system, whereas inspiration is focused more on learning about the biological system on a deeper level. Table 2 summarizes the biological inspiration affinity sort. The categories of tendons and muscles include concepts that illustrate deeper learning of how the frog's legs propel it forward when jumping. The leg strength category illustrates the blending of learning and copying the frog legs, whereas the legs category concepts focus exclusively on the physical characteristics of the legs. Examples from the category other include frog bones, frog posture, and jumping distance. Figure 5 provides two representative examples of student work from the affinity sort that align with the categories given in Table 2.

Table 2: Affinity Sorting of Biological Inspiration

	Tendons	Muscles	Leg Strength	Legs	Other
Total	38	9	11	20	10
BI	9	1	**7**	**15**	**8**
CK	**29**	**8**	4	5	2
Inspiration VS. Imitation	🟦	🟦	🟪	🟥	🟥

Biological system: Northern Leopard Frog

Biology Knowledge
• catapult-like mechanism
• storing elastic energy
• shows patterns of muscle length change and joint motion observed in the Plantaris.
• tendon recoil to power ankle extension.

Unexpected Property
Northern leopard frogs stretch their tendon to store work by muscle contraction, following release of energy during the jump.

Abstract:
The frog uses all four legs to jump forward. It mostly extends its longer rear legs to propel forward and guides or lands with its front legs. The frog also swims using all four legs. The motion is that of a breast stroke.

Figure 5: Example Student Work for Biological Inspiration Affinity Sort. Left: Tendons Example. Right: Legs Example.

Engineering implementation data was determined from the traditional knowledge box and the sketch of the C-K map and steps of the creating phase of the of the biomimicry design lens. Table 3 summarizes the engineering implementation affinity sort. The category connects to existing technology includes concepts that include technology that is feasible and on the market, such as leg press mechanisms. The elastic/kinetic energy category includes concepts that focus on the tendon and muscle functions of energy storage and release primarily through springs or elastic bands. The frog motion category includes concepts that require the rider to move like a frog or the vehicle moves like a frog. Concepts in the category other do not provide enough information to discern if it fits within another category. Some concepts were not bio-inspired and one was not human powered. Figure 6 provides two representative examples of student work from the affinity sort that align with the categories given in Table 3.

Table 3: Affinity Sorting of Engineering Implementation

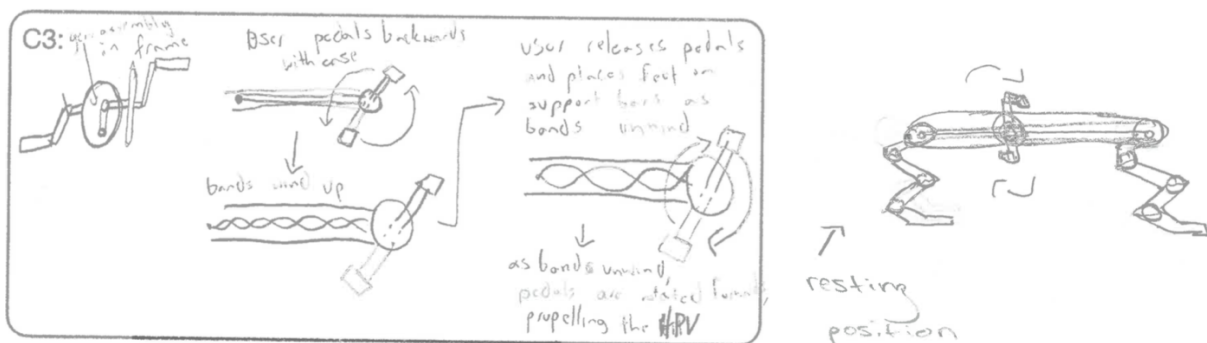|	Connects to existing technology	Elastic/Kinetic Energy	Frog motion	Other	Not Bio-inspired	Not a HPV
Total	28	32	14	4	9	1
BI	10	13	**9**	2	**5**	**1**
CK	**18**	**19**	5	2	4	0

Figure 6: Example Student Work for Engineering Implementation Affinity Sort. Left: Elastic/Kinetic Energy Example. Right: Frog Motion Example.

To further investigate the research question, a quantitative analysis was performed on the scores assigned to each concept. Each concept was scored by two raters on a 0-3 scale for the metrics of biomimicry and feasibility. The scoring for the biomimicry metric is as follows: 0 for directly copying the biological system, 1 if between a direct copy and information extraction, 2 if biological information was extracted, and 3 if biological information was abstracted. The scoring for the feasibility metric is as follows: 0 for not technically feasible, 1 if feasible but difficult for the context, 2 if not difficult for the context and not existing outside the dataset, and 3 if existing outside the dataset [44]. The two scores were averaged and parametric (student t test) and non-parametric (Wilcoxon-Mann-Whitney Rank Sum) statistical tests were performed on the averaged values. Table 4 summarizes the statistical results. The probability values indicate the confidence that the differences between mean scores for each criterion are significantly different.

Table 4: Mean and Probability Values for Statistical Tests

	Mean scores (N)		p values	
	C-K	BI	Student t test	Wilcoxon-Mann-Whitney Rank Sum
Biomimicry	1.57609 (47)	1.09459 (41)	p=0.003268	p=0.00584
Feasibility	2.15217 (47)	1.74324 (41)	p=0.01319	p=0.01235

5.2 Task 4 – Individual reflection questions about the content and process

Both populations were required to answer both Likert scale and open-ended reflection questions as part of the assignment. Table 5 provides the question sets.

Table 5: Reflection Questions of Task 4

Likert Scale Questions	**Open-ended Questions**
Q1: How effective was the bio-inspired design approach taught in class in helping you to identify a biological organism to help solve the engineering design task?	What did I learn about the content (biology)?
Q2: How effective was the bio-inspired design approach taught in class in helping you to understand the underlying principle of the biological organism?	How did I learn the content?
Q3: How effective was the bio-inspired design approach taught in class in helping you to transfer knowledge learned from a biological organism to the engineering design task?	What am I going to do with the content?
Q4: How effective was the bio-inspired design approach taught in class in helping you to apply the biological inspiration to your engineering design task?	
Q5: How effective was the design approach overall in demonstrating the value of biology as a resource for finding solutions to engineering design problems?	What did I learn about the process

	(bio-inspired design)?
Q6: How effective was the design approach in motivating you to learn more about how biological systems have solved problems in different engineering categories?	How did I learn the process?
Q7: How engaged were you in learning the bio-inspired design process?	What am I going to do with the process?

For each of the Likert scale questions, students were instructed to answer on a scale of 1 to 5 (1 being low, 3 being neutral, 5 being high). The responses were averaged and are reported in Table 6.

Table 6: Mean Values of Responses to Likert Scale Questions of Task 4

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
BI	4.01	3.88	4.00	3.92	4.46	4.14	4.17
CK	3.98	3.91	3.98	3.97	4.42	3.98	4.15

5.3 Discussion

Affinity sorting resulted in distinct trends between the two groups. Students from the C-K group tended to take inspiration from non-observable biological information (e.g., how the tendons and muscles function). Meaning they learned information beyond the surface level about what allows the frog to propel itself. When applying the biological inspiration, they were more likely to utilize existing technology such as rowing machines, leg presses, elliptical machines, and crank arms in their concepts as well as abstract the functional characteristics of the biological inspiration. This demonstrates the ability to make connections across the domains for practical applications. Students in the BI group tended to fixate on the number, shape, strength or motion of the frog legs. They were also more likely to generate concepts that imitated how the frog looks or acts or requires the user to act like a frog. While the BI group was more likely to generate unique ideas, they were also more likely to generate concepts that are not relevant to the process or problem.

Statistical analysis of concepts using an objective scoring method supports the trends observed through affinity sorting. Statistical significance was achieved for the hypothesis that the C-K approach would produce higher quality concepts than the Biomimicry Institute approach. Statistical significance was found at $p=0.01$ (both tests for biomimicry metric) and $p=0.05$ (both tests for feasibility metric). Meaning the C-K group produced concepts that were more biologically inspired and technically feasible.

In this preliminary analysis, it was found that the C-K group produced results of higher quality through multiple analyses. Connections between biology and engineering are influenced by alignment with mental representations or mental models [45]. Mental models influence the level of abstraction that designers use when transferring knowledge across domains. We cannot

explain why certain biological information or engineering implementation was dominant over others with respect to the student concepts; however, the data shows that when visually guided through the thought processes of bio-inspired design with the C-K map students fixated less on irrelevant information. As compared to the BI group, the C-K group made deeper connections between biology and engineering for problem solving. The C-K mapping template provides a visually guided approach and allows a novice designer to map the mindset of bio-inspired design.

Interestingly, the results of the self-reported perception on the effectiveness of the bio-inspired design approach learned are the same between both groups for five of the seven questions. Students in the C-K group rated Q5 and Q6 lower which is opposite of the task 1 analysis results. This could be due to the fact that the C-K mapping template focuses on a single biological system at a time. Students reported that the methods helped them to understand the biological system and transfer the knowledge learned to the engineering design task. Meaning cross-disciplinary connections were made to facilitate problem solving. Students seem to enjoy the topic of bio-inspired design regardless of the method taught. Overall, students recognized the value of taking inspiration from nature for solving engineering problems, and many would use the approach again in future classes or projects.

6. Conclusions and Future Work

This paper reports on the preliminary analysis results from testing the hypothesis that the C-K approach would result in higher quality design concepts. It was found that the C-K group generated concepts that more closely resembled biological inspiration, meaning learning from nature to innovate rather than copying, and successfully abstracted biological system principles to create high quality concepts. Whereas the BI group generated concepts that more closely resembled biological imitation, which tended to fixate on observable features and produced concepts that look or act like the biological systems. Statistical significance was achieved for the hypothesis using the metrics of biomimicry and feasibility. The study findings provide conclusive evidence of learning impact and support design theory based bio-inspired design pedagogy. Integrating bio-inspired design with the traditional design curriculum has numerous benefits, but teaching methods are limited. We believe the results of this research can inform engineering educators on how to effectively teach bio-inspired design to engineers.

Future work includes statistical analysis of the task 2 concepts and qualitative content analysis of the open-ended reflection questions. The responses to the open-ended questions will be analyzed using a qualitative content analysis approach to provide contextual information to the quantitative data [46]. Responses will be reduced to their smallest meaningful unit and given a code. Codes will be grouped into categories followed by definition of themes from the categories. Additional future work includes testing the C-K theory-based instructional resources at other institutions to evaluate transferability.

7. Acknowledgements

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