Evidence-based Resources that Scaffold Students in Performing Bio-inspired Design

Dr. Jacquelyn Kay Nagel, James Madison University

Dr. Jacquelyn K. Nagel is an Assistant Professor in the Department of Engineering at James Madison University. She has eight years of diversified engineering design experience, both in academia and industry, and has experienced engineering design in a range of contexts, including product design, bio-inspired design, electrical and control system design, manufacturing system design, and design for the factory floor. Dr. Nagel earned her Ph.D. in mechanical engineering from Oregon State University and her M.S. and B.S. in manufacturing engineering and electrical engineering, respectively, from the Missouri University of Science and Technology. Dr. Nagel's long-term goal is to drive engineering innovation by applying her multidisciplinary engineering expertise to instrumentation and manufacturing challenges.

Dr. Ramana Pidaparti, University of Georgia

Ramana Pidaparti, is currently a Professor of Mechanical Engineering at VCU. Dr. Pidaparti received his Ph.D. degree in Aeronautics & Astronautics from Purdue University, West Lafayette in 1989. In 2004, he joined the Virginia Commonwealth University as a Professor of Mechanical Engineering. He has taught previously at Purdue University campus in Indianapolis (IUPUI). He has taught several courses in design, mechanics of materials, optimization, and directed many interdisciplinary projects related to design. Dr. Pidaparti's research interests are in the broad areas of multi-disciplinary design, computational mechanics, nanotechnology, and related topics. Dr. Pidaparti has published over 250 technical papers in refereed journals and conference proceedings. Dr. Pidaparti received a Research Initiation Award from the National Science Foundation and the Young Investigator Award from the Whitaker Foundation. He is a member of Tau Beta Pi, Sigma Gamma Tau, and Who's Who societies. He is a member of professional societies including AIAA (Associate Fellow), AAAS (Fellow), ASME (Fellow), RAeS (Fellow), and ASEE (member). Dr. Pidaparti will move to University of Georgia in January 2014 as a professor of mechanical engineering.

Prof. Christopher Stewart Rose, James Madison University

I do research on the development and evolution of amphibian anatomy and I teach courses on comparative anatomy of vertebrate animals, animal development, human development and evolution, scientific writing, and biology in the movies.

Ms. Elizabeth Marie Tafoya

Elizabeth Tafoya is a fourth year engineering student at James Madison University. In addition to engineering, Elizabeth has a minor in geology. She has participated in Bio-inspired Design for Dr. J Nagel since the Spring of 2017 to further her interests in design processes.

Mr. Prabaharan Graceraj Ponnusamy, University of Georgia

Tyler Jeffrey Wahl, James Madison University

I am a student from James Madison University who is majoring in Engineering and Minoring in Mathematics. My current interests within the degree of Engineering are found in the Sustainability and Environmental field, but I also find myself wanting to explore the Biomedical and Mechanical fields as both have held my attention in the past. Outside of my academic life, I enjoy any outdoors activity including hiking, biking, and kayaking, along with playing my two favorite sports, basketball and volleyball. But whether I am studying in the department or out and about on campus, I always try to strengthen the connections I have with my friends and family, and spend any free time I can with them. The connections i have made in college are the most valuable parts of my life, because my friends and family have helped shape who I am, and they make me a better person every day. I owe my fortune of becoming an engineer and achieving my dream of helping people to all my friends and family for inspiring me to be me.

Ms. Jessica Besnier, James Madison University

Ms. Jordan Claire Capelle, James Madison University

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Introduction

Undergraduate education must train students to solve engineering challenges that transcend disciplinary boundaries, but must also train students to communicate, transfer knowledge, and collaborate across technical and non-technical boundaries to address the competencies of the future engineer. 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 affective hook to frame complex, cross-disciplinary problems. This research focuses on the development of instructional resources that provide exposure to the abundance of design examples that can be found in nature, as well as scaffold the discovery and knowledge transfer processes such that those natural designs can be used to inspire engineering solutions. The project work period is Fall 2015 to Summer 2019. Design theory, specifically Concept-Knowledge (C-K) Theory is used as the basis for the instructional resources. 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.

The instructional resources have been deployed at two predominately undergraduate institutions (PUIs) in the second-year engineering curriculum. The learning impact of the instructional resources was evaluated in two ways: (1) a comparative study of the C-K method against the popular Biomimicry Institute method, and (2) an impact study using a combination of correlation analysis and principle component analysis of the biomimicry and design learning attributes. Both studies resulted in significant results. Statistical significance was achieved for the hypothesis that the C-K method would produce higher quality solutions than the Biomimicry Institute method. This hypothesis was tested using parametric (student t test) and non-parametric (Wilcoxon-Mann-Whitney Rank Sum) tests for each of the four metrics and the cumulative score of the four metrics. The results of correlation analysis based on University of Georgia and James Madison University students indicated that that the biomimicry process attributes- biological knowledge, defined dichotomy, defining rough ideas, and transition from rough idea to sketch– had strong positive influence on the specific design engineering attributes of – imagination, innovation, and design solution definition. These relationships demonstrate that the design solutions can be innovative following C-K theory. These correlations also provide evidence to further the belief that biomimicry is a significant approach to enhancing engineering curricula. Our instructional resources have resulted in design concepts that more closely resembled biological inspiration, learning from nature to innovate rather than copying, as opposed to biological imitation that closely resembles the observable features of biological systems.

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 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].
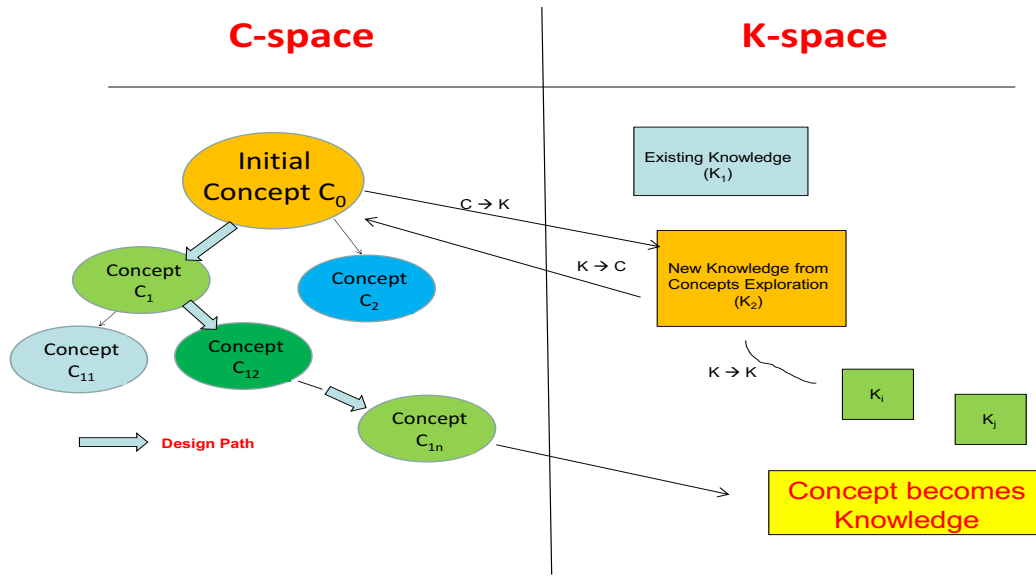
Figure 1: C-K Theory Framework

There are four operations allowed: concepts being used to generate new concepts ($C{\rightarrow}C$), 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 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. 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.

Research Progress

Progress toward both research objectives has been made at both James Madison University (JMU) and University of Georgia (UGA). A summary of research progress is given in Table 2.

Table 2: 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
	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
	c. Disseminate evidenced-based instructional resources through publications and global educators networks.	ASEE presentation[7]; journal publication[8]; Book chapter (in review); Plenary Talk at the 11th International Workshop on Design Theory; ASEE 2019 Workshop Biomimicry Educators Network contribution
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 and UGA; Principal Component and Correlation Analyses for JMU and UGA
	c. Assess student ability to create bio-inspired designs.	Student artifact analysis for JMU and UGA; Comparative study of C-K approach to Biomimicry Institute approach

The instructional resources created using the C-K theory framework are outlined in Table 3. Through integration of C-K theory with instructional scaffolding, the instructional resources accommodate diverse student learning styles and abilities.

Table 3: Summary of Created Instructional Resources

Instructional Resource	Description
Teaching Modules	Modules scaffold the knowledge transfer processes between domains, model adaptive expertise, model development of cross-domain linkages and utilize analogies. Modules are in the form of lectures and case studies.
Learning activities	Students engage in scaffolded, in-class exercises that promote active learning.
Assignments	Students practice developing cross-domain linkages to and from biology for solving engineering problems.
Design Project	Students 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 [9], was employed to create the instructional resources. The focus is student-centered and ensures mastery through continuous feedback. Furthermore, the resources are designed such that they can be easily integrated into existing engineering curricula. Experts in education, biology, and engineering design assisted with designing the instructional resources. The developed instructional resources [7] have been deployed at two predominately undergraduate institutions (PUIs) in the second-year engineering curriculum.

Analysis and Results

The results at the time of this publication are focused on objective two. Prior publications describe the results of objective one.

Qualitative and quantitative data analysis from a Fall 2016 controlled experiment at JMU provides evidence of learning impact for the C-K theory based approach. The experiment was conducted across multiple course sections to test the C-K theory based approach against the

popular Biomimicry Institute approach. To quantitatively evaluate the student bio-inspired design concepts created using both approaches, a set of scoring metrics are created. The metrics chosen are biomimicry, feasibility, practicality, and novelty, and were established from the literature reviews on concept evaluation metrics and based on the goal of creating a method that produces high quality solutions that are technically feasible and not science fiction. To increase objectivity, the metrics are created using an accepted flow-chart format as found in literature that assigns points to the answer of a set of three questions. Statistical significance was achieved for the hypothesis that the C-K method would produce higher quality solutions than the Biomimicry Institute method. This hypothesis was tested using parametric (student t test) and non-parametric (Wilcoxon-Mann-Whitney Rank Sum) tests for each of the four metrics and the cumulative score of the four metrics. Details of the analysis can be found in a companion ASEE 2019 publication [10].

In addition to quantitative analysis of student bio-inspired design concepts, reflection essay responses about the content and process are processed using a qualitative content analysis technique to identify themes. This work is completed manually as well as using the software NVivo. The goal of using the software for analysis is to auto code the data to verify the themes found manually as well as identify any that are overlooked. Analysis using NVivo is still in progress. The results of this analysis will be shared in a journal publication.

Analysis of the C-K mapping data from the Fall 2016 is also included in an impact study that evaluates the biomimicry and design learning attributes of JMU and UGA students. The impact study uses a combination of correlation analysis and principle component analysis. Statistical analysis is conducted to map the relationship between biomimicry attributes and design attributes and comparing them between UGA and JMU students. The results of the correlation analysis indicate that the biomimicry process attributes–Biological knowledge, Defined dichotomy, Defining rough ideas and Transition from rough idea to sketch–had strong positive influence on the design engineering attributes of–Imagination, Innovation and Design Solution Definition. The preliminary results are published in the 2018 ASEE SE Conference [11]. The full results of this analysis are currently being written for a journal publication.

Conclusion and Future Work

Significant results for objective two are reported. The learning impact was evaluated in two ways: (1) a comparative study of the C-K method against the popular Biomimicry Institute method, and (2) an impact study using a combination of correlation analysis and principle component analysis of the biomimicry and design learning attributes. Statistical significance was achieved for the hypothesis that the C-K method would produce higher quality solutions than the Biomimicry Institute method. This research also resulted in identification of strong correlation between biomimicry and design learning attributes. These relationships demonstrate that the design solutions can be innovative following C-K theory. These correlations also provide evidence to further the belief that biomimicry is a significant approach to enhancing engineering curricula.

The impact on engineering education is in the creation of evidence-based instructional resources that lower the hurdle for engineers to use bio-inspired design as a problem solving lens and

approach to develop innovative solutions, as well as produce high quality solutions that are technically feasible and not science fiction. The instructional resources address the need for undergraduate student training in multidisciplinary design innovation that provides students with the essential competencies they will need to meet the complex challenges of future problems. The concept evaluation metrics aid instructors in evaluation of the quality of the bio-inspired designs regardless of method used to create the concept.

The impact on bio-inspired design is twofold: exposing more engineers to the abundance of design examples that can be found in nature, which demonstrates the utility of the approach, and equipping engineers with a theory driven approach for applying bio-inspired design in problem solving. Both impacts promote the broader adoption of the approach in the field of engineering. Progress has been made toward the research objectives. Future work will focus on the dissemination of the instructional resources.

Acknowledgements

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