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Teaching bioinspired design using C–K theory

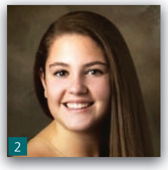
1 **Jacquelyn K. Nagel** PhD*
Assistant Professor of Engineering, James Madison University, Harrisonburg, VA, USA

2 **Peyton Pittman**
Undergraduate Engineering Research Assistant, James Madison University, Harrisonburg, VA, USA

3 **Ramana Pidaparti** PhD
Professor of Engineering, University of Georgia, Athens, GA, USA

4 **Chris Rose** PhD
Professor of Biology, James Madison University, Harrisonburg, VA, USA

5 **Cheryl Beverly** PhD
Professor of Learning, Technology and Leadership Education, James Madison University, Harrisonburg, VA, USA


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 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 training engineers in these competencies is teaching biomimicry or bioinspired 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 aims to address the need for undergraduate student training in multidisciplinary design innovation through the creation of instructional resources grounded in the concept–knowledge theory that scaffolds discovery and knowledge transfer processes such that natural designs can be used to inspire engineering solutions. Qualitative content analysis of second-year engineering student reflection statements shows that the instructional resources resulted in significant learning and engagement.

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 the society is moving 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 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 at 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 bioinspired design in an engineering curriculum.[5] Bioinspired design encourages learning from nature to generate innovative designs for man-made technical challenges that are more economical, efficient and sustainable than the ones conceived entirely from first principles.[6]

Incorporating other science, technology, engineering and math (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 secondary school-level training in biology. Adding biomimicry into the engineering curriculum encourages students to utilise and build on their prior knowledge, which fosters making connections and recognising interrelationships across Stem disciplines.[7,8] Moreover, requiring knowledge transfer across domains as well as organising that knowledge into logical constructs helps to develop future flexibility and adaptive expertise that will facilitate

*Corresponding author e-mail address: nageljk@jmu.edu

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 biological information intelligently to engineering problems (which addresses technical skills). Additionally, biomimicry touches on many areas of engineering, including electrical, mechanical, materials, biomedical, chemical and manufacturing systems, which makes it applicable in a wide range of engineering programmes, from discipline-specific to general ones.

Showing engineering students the significance and utility of bioinspired design is easy. Teaching them how to create a bioinspired design without also requiring them to be fully trained as biologists is much more difficult. Teaching bioinspired design in an engineering curriculum relies on either the impromptu 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 guide students effectively 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 they are not supported in the actual leap. Thus, analogy use/misuse, mapping and transfer are repeatedly cited as the major challenges with teaching bioinspired design to engineers.[11–19] This is an important gap to address since effective navigation between engineering design and biology spaces builds connections that facilitate innovative design and increases 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 the concept–knowledge (C–K) theory for implementing bioinspired design in an engineering curriculum, with particular focus on assisting engineering students with knowledge transfer between the domains of engineering and biology.

2. Background material

In this section current approaches to teaching biomimicry in an engineering curriculum are shared as well as background knowledge on the C–K theory, which is used as the basis for the instructional resources.

2.1 Teaching bioinspired design

In response to the increased emphasis on adaptable and sustainable design by professional societies, the industry and today's global marketplace, engineering programmes in the USA and internationally are increasingly expanding the scope and focus of their curricula to include bioinspired design topics and projects. The inclusion of bioinspired design expands cross-disciplinary and system thinking skills and has been integrated into engineering programmes at the module, project or course level.[7,8,11,14–16,18–27] While instruction in bioinspired design is quite common in engineering programmes at the graduate level, it is exciting to note that bioinspired design instruction is also being incorporated into curricula at the undergraduate level.

Multiple institutions offer engineering courses in bioinspired design or interdisciplinary courses that bring together students from Stem and art that span an academic term. Probably the most well-known institution is Georgia Institute of Technology (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 the biology and engineering departments and admits junior- and senior-level students from all fields of engineering and biology. Two processes for bioinspired design, problem-driven and solution-driven, are taught in the course, and analogies are formed through functional decomposition, similar to functional modelling 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. Honours-level undergraduate courses similar to the one at Georgia Tech have been offered at institutions such as Virginia Polytechnic Institute and State University.

The mechanical engineering department at Montana State University offers a senior-level technical elective on bioinspired engineering.[14] The course covers relevant bioinspired 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 University is currently developing an undergraduate course to introduce interdisciplinary engineering students to multiple methods of bioinspired design.[25] The course will be an elective in the mechanical engineering curriculum that focuses on breadth of approach rather than depth, exposing students to the state of the art in bioinspired design research tools and methods. At the Olin College of Engineering, all students take a course that introduces bioinspired design in their first academic term. 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 by using the Biomimicry Innovation Tool, which blends aspects of problem-based learning, innovation, biomimicry and ergonomics into a single student experience. They present their bioinspired 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 programme.[19] Students study biological locomotion and how it can inspire efficient mechanisms of motion.

Non-US institutions that offer courses in biomimicry are concentrated in Europe. Germany alone has 16 universities that offer lectures, seminars, electives, core courses or degrees related to biomimicry or biomimetics.[32] Saarland University offered multiple courses and lectures in the area of technical biology developed by Professor Nachtigall, but these were abandoned following his retirement.[32] Hochschule Bremen offers an international bachelor's degree in biomimetics that blends biological and engineering science through a practice-based, interdisciplinary course of study with courses on materials, structures and transport systems.[33] One course, 'Locomotion', investigates the biological drive mechanisms of animals through the creation of kinematic and dynamic models of technical and natural structures. The course requires laboratory experiments as well as discussion on animal rights' protection policy and ethics.[34] At the University of Bath, fourth-year mechanical engineering students can take a course in biomimetics. Courses on bioinspired materials are offered at Nanyang Technological University in Singapore, ETH Zurich, Eötvös Loránd University in Budapest and KTH Royal Institute of Technology in Stockholm. A unique course on biomimetic biomaterials and technologies for the purposes of medical bioengineering is offered at Grigore T. Popa University of Medicine and Pharmacy in Romania.[35]

Bioinspired design concepts and examples have been used by many institutions to educate students on design innovation and as another source of design inspiration. These institutions include Oregon State University, University of Georgia (UGA), James Madison University (JMU), Purdue University, Clemson University, Penn State University–Erie, University of Maryland, Indian Institute of Science, University of Toronto, Dalhousie University, Freiburg University and École 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 bioinspired design to practice the technique and demonstrate its value. Integration occurs at the freshman through the senior level, in a variety of departments, and primarily depends on when engineering design is offered in the curriculum. Consequently, varying levels of instruction and support are provided to the students, and many rely on the resources provided by the Biomimicry Institute, such as the database AskNature.org. This points to the lack of engineering-focused, evidence-based instructional resources available to faculty that wish to integrate bioinspired design into their courses.

2.2 C–K theory

The C–K theory, introduced by Shai *et al.*,[36] Hatchuel *et al.*[37] and Hatchuel and Weil,[38] integrates creative thinking and innovation by utilising two spaces: (*a*) the knowledge space (K), a space containing propositions that have a logical status for the designer, and (*b*) the concept space (C), a space containing concepts that are propositions or groups of propositions that have no logical status (i.e. are undetermined) in K.[36–40] This means that when a concept is formulated, it is impossible to prove that it is a proposition in K. Rather, concepts are used to 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, the C–K theory has shown to reduce fixation and improve the knowledge and creativity of the user.[36–40]

There are four operations allowed: expansion of each space ($C \rightarrow C$, $K \rightarrow K$); conjunction, meaning when a concept proposition is tested and leads to new knowledge ($C \rightarrow K$); and disjunction, meaning when a new concept is 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 into the parent set. After partitioning or inclusion, concepts still remain concepts ($C \rightarrow C$), but they can also lead to the creation of new propositions in K ($C \rightarrow K$). The combination of knowledge and addition of new discoveries expands the knowledge 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: using the addition of new and existing concepts to expand knowledge and using knowledge to expand concepts. The C–K theory thus provides a framework for a designer to navigate the unknown, to build and test connections between the knowledge and concept spaces (analogies) and to converge on a solution grounded in theory combined with new knowledge.

The C–K theory emphasises 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; rather, it is being leveraged to improve understanding of innovative designs. Moreover, the C–K theory requires explicit documentation of the design path, thus inherently modelling cross-domain linkages. Utilising the C–K theory to create instructional resources for teaching bioinspired design that integrate biology, engineering and design establishes a two-way connection between engineering and biology and illustrates how knowledge transfer processes can lead to design innovation. The C–K theory is adaptive and generalisable across scientific domains, which makes it amenable to a wide range of engineering problems as well as programmes.

3. Experimental

Utilising the C–K theory to create instructional resources for teaching bioinspired design that integrates biology, engineering and design establishes a two-way connection between engineering and biology and illustrates how knowledge transfer processes can lead to innovative solutions.[41] Although the C–K theory is an established theory, no instructional resources for how to use it in a classroom exist; thus, a major part of this research was to design the instructional resources themselves. Because the C–K theory is a visual approach to structuring the discovery process of learning from the knowledge and concept spaces, a C–K mapping template (as shown at the top of Figure 1) was created. This template is an adaptable instructional resource that promotes discovery by facilitating the knowledge transfer processes of bioinspired design going from biology to engineering (biology-driven direction) as well as from engineering to biology (problem-driven direction) if starting from the knowledge or concept side, respectively. An accompanying set of guidelines for filling out the template was created to assist novice learners. As an adaptable resource, the template can be used at multiple learning levels (e.g. novice, intermediate, expert) by adding or subtracting supplemental information and by choice of design path. The instructional resources created using the C–K theory framework are outlined in Table 1.

In fall of 2015, the lead author instructed a second-year engineering design course (total n = 23) that incorporated each

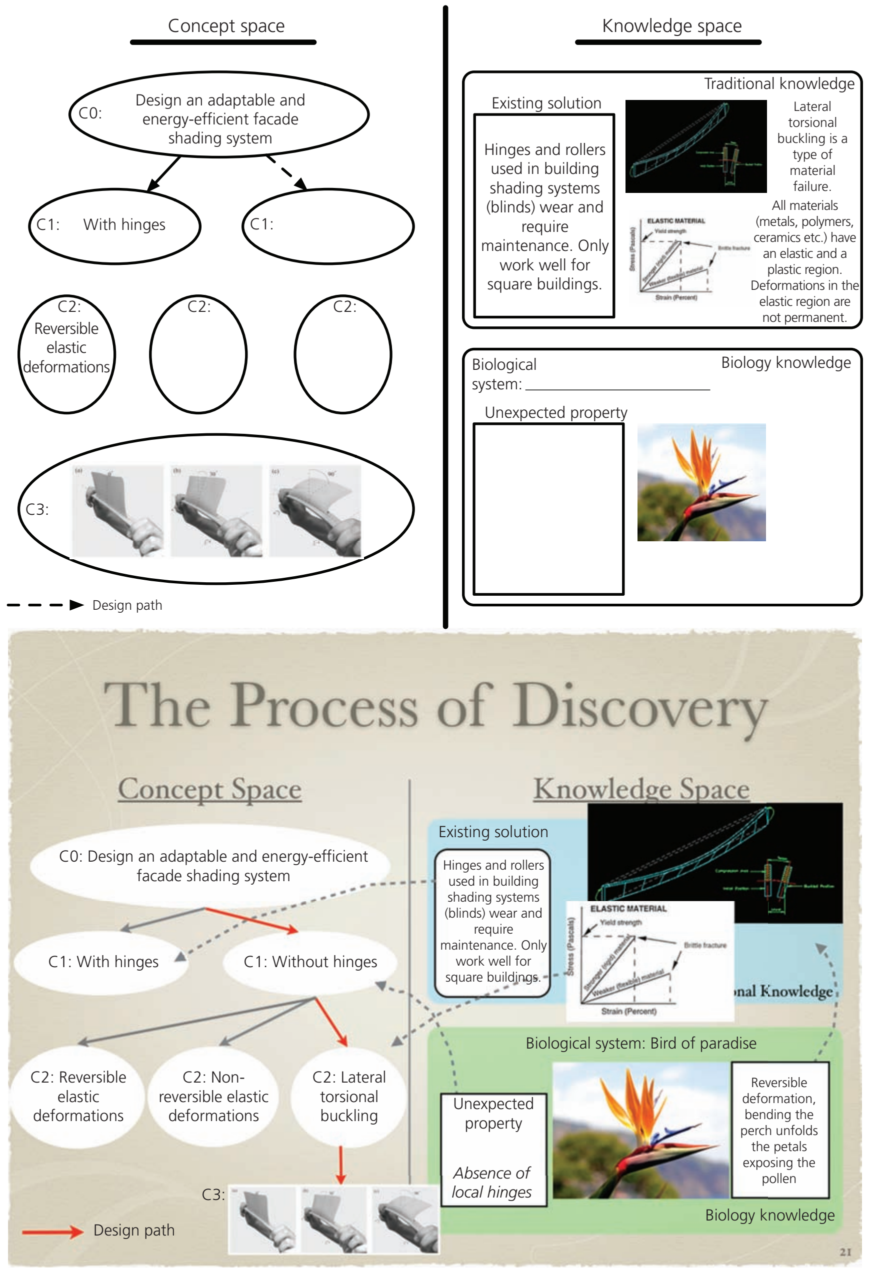


Figure 1. Template (top) and slide (bottom) from teaching module for first learning activity

Instructional resource	Description
Teaching module	Demonstrates the breadth of biological inspiration, models the development of cross-domain linkages, scaffolds the knowledge transfer processes between domains and utilises analogies
C–K mapping template and guidelines	Guide students through the two major paths to a bioinspired design (biology-driven and problem-driven) and scaffold the knowledge transfer processes between domains
Learning activities	In-class exercises that promote active learning of bioinspired design
Assignments	Students practice developing cross-domain linkages to and from both domains for solving engineering problems

Table 1. Summary of instructional resources

instructional resource listed in Table 1. The second-year engineering design course focuses on the theory, tools and methods of the engineering design process. Students work in teams to design a human-powered vehicle (HPV) for a person in the community with cerebral palsy.

The developed teaching module introduces bioinspired design as a design philosophy and provides several examples of how biological systems were used as inspiration for innovative solutions. Students learn about the two major paths to a bioinspired design, biology-driven and problem-driven, as well as how analogies are used to assist with transferring the knowledge from biology to engineering. To scaffold the students in their application of bioinspired design, two problem-driven examples using the C–K theory were provided with accompanying learning activities using the C–K mapping template. The first learning activity focused on the hingeless facade shading mechanism, Flectofin, inspired by the bird of paradise flower.[42] Shading buildings with irregular geometries is very difficult since most sun protection systems have been developed for planar facades and include the use of hinges. The pollination mechanism of the bird of paradise flower offers inspiration based on the elastic kinematics of plant movements. After the initial problem is explained, students are provided a partially filled-in template to complete during the explanation of the example as shown in Figure 1. This scaffolds the students through the C–K theory mapping process without burdening them with the theory. Students are walked through the thought processes and analogies of the discovery process for arriving at a bioinspired solution by using the C–K theory framework as shown in Figure 1. The slide animations build up the information and demonstrate the four types of operations ($C \rightarrow K$, $K \rightarrow C$, $K \rightarrow K$, $C \rightarrow C$) that capture all known design properties, including creative processes, and explain the chaotic, iterative nature of real and practical design work starting from the C0 level and arriving at the C3 level in the concept space. Furthermore, the grey dashed arrows provide insight on how concepts are elaborated by using knowledge and when the operators are used. The example concludes with explaining the technical innovation that resulted from the process of discovery.

The second problem-driven example and learning activity is focused on the propulsion subsystem of an HPV. This is meant to scaffold the students in not only using the template, but also recognising how the approach can be applied to their course project in a meaningful way. During this learning activity, the students were provided a blank copy of the C–K mapping template and a copy of the guidelines. Students work in small teams with more independence this time and work through each step of the guidelines while the instructor roams the room to answer questions. If several students are struggling, the instructor addresses key points in the process of filling out the template with the whole class. When most teams have completed the step, the next layer of information is shown on the slide to demonstrate how an expert would go through the process and to discuss how the connections or linkages are formed between biology and engineering. Again, the slide animations build up the information and demonstrate the four types of operations that capture all known design properties, including creative processes, and explain the chaotic, iterative nature of real and practical design work.

All assignments in the second-year engineering design course tie to a year-long course project of developing an HPV for a client in the community that has cerebral palsy; thus, a separate project was not defined for this implementation. To integrate bioinspired design into the HPV design project, each member of a team applied bioinspired design to a different subsystem (e.g. propulsion, steering, braking) of their design to showcase a variety of design problems and analogies that enable bioinspired design. All students 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 HPV. The developed assignment that complements the teaching module and learning activities for the second-year engineering design course includes three tasks: (*a*) completing the C–K mapping template for an HPV subsystem, (*b*) using the sketches at the C3 level of the template along with the team-generated morphological matrix to create a fully HPV concept and (*c*) a W/H/W reflection essay answering three questions about the content and process. The W/H/W reflections require learners to reflect on and respond to three questions: ‘What did I learn?’, ‘How did I learn it?’ and ‘What will I do with it?’ These three prompt the second problem-driven example structure reflection so that learners focus on concepts, knowledge, skills, processes and engagement of learning. The W/H/W reflections provide formative snapshots of learning and application to explore the connections across concepts and domains that learners are making as they progress through the material.

For this paper, the W/H/W reflection questions were analysed to identify trends in student learning outcomes in bioinspired design education in an engineering design course. Fifteen (65%) students consented to participate in the research. Transcriptions of the reflection questions for consenting participants were de-identified and analysed by using qualitative content analysis. Qualitative content analysis identifies themes in the student reflections. This involved reducing the participants' comments to their smallest meaningful units, coding these units, grouping the coded units into categories and then grouping the categories into different themes.[43,44] The following section presents the results of the qualitative content analysis and a discussion of the findings.

4. Results and discussion

The student responses to the six reflection questions resulted in 206 (108 for content questions and 98 for process questions) unique/coded meaningful units. Multiple themes and categories emerged for each question based on coded meaningful units. Tables 2 and 3 show the coded meaningful units produced for each reflection question as they were grouped by category (N = number of supportive coded meaningful units in each category) and theme (N = number of supportive categories in each theme). The qualitative content analysis shows the trends in student responses through aggregated data such that identity of the student is protected.

Each question has one or more highly supported themes ($N > 10$) and one theme with less support ($N < 10$). The highly supported themes related to learning about content (biology) are that students learned detailed information about their chosen biological system, established cross-domain linkages and overall valued what can be learned from biology and applied to engineering problems. Most categories found under these themes were fully anticipated. One unanticipated category from one student was that learning about biology helped in gaining further knowledge about a specific subsystem of the HPV. In other words, the assignment allowed the student to learn more about engineering through biology. Students learning the content through non-course resources was anticipated, as the instructional resources did not provide that information. Also, with respect to what students will do with the content, application to the course project through the assignment was anticipated. It is encouraging that some students recognised other applications of the learned content.

The highly supported themes related to learning about the process (bioinspired design) are that students valued the inclusion of biological inspiration during the design process and that inspiration from nature can help solve design problems, even though sometimes more analysis is required than initially thought. It was anticipated

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 (17)	T1: Scholarly or external resources (31)	T1: Apply to immediate problem – class project (16)
Nature has surprisingly complex systems that work well in particular since they have been around for years (7)	Further exploration or analysis of information beyond website provided (21)	Apply to class assignment – HPV (12)
Nature has a lot to offer for potential solutions (5)	Independent research using website provided (9)	Maybe apply it to class (HPV) but question feasibility or necessity (4)
Nature has attributes that can be iterated easily into design (5)	Discovery Channel television special (1)	
T2: In-depth understanding of chosen biological system (14)	T2: Course learning resources (4)	T2: Facilitate a future design path (11)
Detailed biological information on specific topic (11)	Class examples (1)	Apply to other problems (6)
Gained knowledge about biological subsystems (3)	Filling out C–K mapping template (3)	Gain new perspective when designing (4)
T3: Cross-domain linkages (11)		Put it on a C–K map (1)
Formed a connection between HPV design and chosen biological subsystem (10)		
Gained further knowledge about specific subsystem of HPV (1)		
T4: Biology is not always applicable (4)		
Biology does not relate to class assignment (3)		
Nothing (1)		

Table 2. Themes and frequencies of content 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: Valued the inclusion of biology in engineering design (22)	T1: Course learning resources (20)	T1: Facilitate a future design path (20)
Keeps the design space open to more ideas (12)	Using the C–K mapping template (11)	Use it when designing or problem-solving in the future (14)
Bioinspired design is a process similar to the engineering design process (10)	Following the class example (8)	Use method to expand design space (3)
T2: Recognised knowledge transfer between domains for problem-solving is possible (17)	Transforming the template information into a drawing (1)	Use existing biology knowledge to help understand engineered components and systems (2)
Biology can inspire solutions to problems (10)	T2: External or other resources (13)	Use in all aspects of life (1)
More biological analyses are needed than anticipated (5)	Previous knowledge (5)	T2: Apply to immediate problem – class project (3)
Facilitates connecting an engineering sub-system to a biological system (2)	Independent research of online resources (5)	Use for class assignment – HPV (2)
T3: Bioinspired design is not always applicable (3)	Applying an engineering problem-solving approach (2)	Continue research (1)
Sometimes bioinspired design is not feasible (2)	Existing bioinspired designs (1)	
Nothing new (1)		

Table 3. Themes and frequencies of process reflection questions

that students would learn the process through course instructional resources, as the instructional resources were created for that purpose. Students were engaged in the learning of bioinspired design as evidenced by the majority of responses linking to future design applications. An unanticipated category from two students was that using existing biology knowledge helps to understand engineered components and systems, which was also found in a student response to what was learned about the content. This emergent trend was unexpected and points towards the significance of teaching bioinspired design in an engineering curriculum.

Comparison of the responses between Tables 2 and 3 by type of question reveals a positive influence of the C–K theory-based instructional resources. The strongest supported themes link well to the objectives of the research, which are to facilitate the knowledge transfer process of bioinspired design, to assess engagement in learning and to increase students' abilities to recognise and formulate interrelationships across disciplinary boundaries and to create bioinspired designs. The reflection analysis indicates that the assignment exposed the students to a variety of design examples in nature, scaffolded the discovery and knowledge transfer processes required to create bioinspired designs and promoted significant learning about biology and applying biology during design as well as engagement. Also, the bioinspired design teaching module, learning activity and assignment were generally well received by students based on reviews of the student assignments and from conversations with the students outside of class. Students found the topic and the C–K mapping process engaging and useful. Many commented in their reflection essays that they found the technique valuable and will use it in future opportunities that require innovative solutions or problem-solving. Additional positive trends in the essays include students commenting that they had never considered nature as a source of design inspiration before and that this process opened up their eyes to so much potential, how impressed they were with the variety of biological systems that can inspire innovations and feelings of creativity and that it was fun or exciting. The only negative category in the essays was the feeling that bioinspired design was not necessary for, or applicable to, the task at hand, and this category was weakly supported ($N = 4$ and 3).

A variety of supportive methods were used to ensure access to information and engagement and encourage students to use their opportunities to engage. The information was presented using multiple modalities including verbal, visual and kinaesthetic. The lecture engaged the whole class, while the in-class activities facilitated smaller-group and individual work. Guided practice was used in class during the activities and independent practice was required in the assignment. One alternative teaching method would be to have a biology faculty member teach biological phenomena in terms of structure–function relationships, much the same way that these are taught in comparative anatomy classes, and have the students use these as the background for abstracting the engineering principle and finding an application.

This paper summarises the progress to date that has been made at JMU with implementation plans for UGA. Analysis of the reflection statements is complete. Future work includes developing a rubric for grading the student-generated bioinspired designs that were produced in the assignment by using C–K mapping templates. This rubric would be designed to score the depth and detail of the student effort to generate a design from a biological example, as well as the plausibility of the final design from an engineering point of view. This rubric would also allow for comparisons between what students actually accomplished and how they perceived the value of the educational experience in their reflection essays. Additionally, the rubric would allow for comparison of student work across institutions and thus provide an objective measure for judging the transferability of instructional materials between JMU and UGA. Additional future work includes administering two controlled experiments to test the C–K theory-based teaching approach against an alternative bioinspired design teaching method to obtain conclusive quantitative evidence of its learning impact.

5. Conclusion

Engineering students find bioinspired design exciting, and it offers relevance to professional practice as well as an effective hook to frame complex, cross-disciplinary problems. This literature review shows growing support for incorporating bioinspired design concepts in undergraduate curricula and identifies some of the engineering programmes in the USA and internationally that are already incorporating bioinspired design courses into their curricula for students from the second- to third-year levels. While progress is being made in expanding existing engineering curricula to include bioinspired design concepts, little is known about how to teach bioinspired design or to support students in the discovery and knowledge transfer processes that enable design innovation to occur. There is still a need to establish instructional resources and best practices for teaching bioinspired design at the undergraduate level, which this research aims to address.

The C–K theory is used to create instructional resources (teaching module, C–K mapping template, learning activities, assignment), as it is known for integrating multiple domains of information and facilitating innovation through connection building. A C–K mapping template was created that visually structures the discovery and knowledge transfer process, and it was demonstrated that this template is an adaptable instructional resource that can facilitate the knowledge transfer processes of bioinspired design going from biology to engineering (biology-driven) as well as from engineering to biology (problem-driven). An accompanying set of guidelines for filling out the template was created to assist novice learners. The instructional resources were piloted in a second-year engineering design course that teaches the fundamentals of engineering design theory and methodology with a course project focused on designing an HPV. Qualitative content analysis of student reflection statements generated in this course revealed that the instructional resources resulted in significant learning of both biology and bioinspired design, as well as learning engagement and value of the experience.

The authors believe that this research will stimulate additional interest in this area and contribute to developing a database of evidence-based instructional resources, as well as new and effective teaching methods which will enhance the pedagogy of bioinspired design in the engineering curriculum. More generally, the authors believe that this research shows that teaching bioinspired design in an engineering curriculum can help to develop many of the competencies required of the twenty-first-century engineer as well as twenty-first-century skills that are essential to being successful in the global workforce and tackling the cross-disciplinary challenges that lie ahead.[45] Teaching bioinspired design offers the potential to train students not just to explore the biological domain for solutions, but also to have the cognitive flexibility, creativity and adaptive problem-solving skills for exploring any contextual domain from which they might find solutions to complex, cross-disciplinary engineering problems.

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