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Biologically Inspired Design For High School Engineering Students (Work in Progress)

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Introduction

Biologically inspired design (BID) has gained attention in undergraduate and graduate engineering programs throughout the United States, and more higher education institutions are beginning to implement it into their engineering curriculum [1], [2], [5], [6]. However, little has been done to introduce BID concepts more formally into the K-12 education high school curriculum. BID, also known as biomimicry, biomimetics, or bionics, is defined as the study of biological systems and functions that have the potential to be adapted for use to solve challenges faced by humans [7]. BID has the potential to provide a framework to make connections between biological systems and the problems that are addressed by the engineers today. Further, the use of biological examples and analogies through BID can enhance the creativity, innovation, and sustainability of engineered products. Hence, incorporating BID-learning into high school engineering courses has the potential to impact the learning experiences positively. Specifically, teaching and learning the engineering design process (EDP) has gained a lot of attention in K-12 education. The EDP has been redefined and codified in diagrams and specific steps within K-12 standards and curriculum. Due to various curricula in high school engineering courses, the language and process of the EDP varies in its definition, structure, and implementation.

In 2019, the NSF funded a K-12 project entitled *Biologically Inspired Design for Engineering Education* (BIRDEE), to create socially relevant, accessible, and highly contextualized high school engineering curricula focusing on bio-inspired design. The curriculum is designed to integrate bio-inspired design into the engineering design process (EDP) by leveraging analogical design tools, that facilitate a transfer of biological strategies to design challenges. This enables students to understand both the engineering problem and the biological system that could be used to inspire design solutions. BIRDEE curricula integrate bio-inspired design into the EDP by leveraging design tools that facilitate the application of biological concepts to design challenges. This provides a conceptual framework enabling students to define a design problem systematically, resulting in better, more well-rounded problem specifications. During Spring 2022, the curriculum was pilot tested in two 9th grade engineering classrooms across two schools. In this paper, we describe the development of the curriculum, its details, and students' experiences during the pilot testing. Further, we provide preliminary results about students' application of BID integration in the EDP and their experiences utilizing BID as they solved design challenges. We aim to use students' perceptions of the curriculum to inform future revisions and develop more robust research tools to measure the learning objectives.

Curriculum Design Requirements and Constraints

The curriculum was designed to introduce students to the EDP and BID as a method to enhance creativity and sustainability within that context [8]. While the introduction of BID was an important component of the curriculum, it was required to teach the EDP according to current state standards as well. As such, there was a design tension at play from the outset—how do we both teach the EDP to novice designers in challenging environments with little or no prior engineering experience, and teach an exciting and engaging supplemental design process, BID, in a way that enhanced the goals of core standards without distracting from them. In challenging environments with novice students, prior experience [9], literature [10], and teacher feedback from summer professional learning [11], led curriculum designers to consider that students gravitated to physical design and prototyping activities, whereas early design process activities such as problem definition and conceptual design were considered onerous for students, made it difficult to maintain student focus, and could result in classroom management issues. Thus, the design team had to balance time and effort devoted to teaching core EDP learning standards against the novel BID processes that would set the curriculum apart, and balance early-stage design activities with the more engaging physical build aspects in later stages, noting that many core BID activities focused on early-stage creativity. Our experience also suggested that problem formulation stages of the EDP, usually neglected by instructors [9] likely due to the engagement issues, were important for finding and evaluating biology relative to the specific design problem [12], according to BID design theory and practice. Another wrinkle in curriculum design was that BID design theory suggests an alternative bio-inspired design approach called solution-driven design, which runs against standard EDP practice. Solution-driven design in BID is the proverbial "hammer looking for a nail" where instead of a hammer, student designers fixate upon a source of biological inspiration, and then designers seek a problem for which the biological solution may work [13]. While this is a legitimate and successful approach in BID, it is not typical in routine engineering design, nor does it comport with existing engineering standards.

The curriculum design was further complicated by the need to ensure that the problem domain would yield biological sources of inspiration that students in the target environments could relate to, where the underlying science principles of those biological solutions could be understood by both student and teacher, where they could be transferred in practice by students to the design context, and where the problem itself encouraged inclusivity [14]. Design problems are not universally equivalent with respect to their ability to yield to BID methods [15]. This constrained the nature of the design problem itself and would limit student agency in problem selection. Besides engineering and design considerations, we wanted to develop a curriculum that established a deeper connection between students and the biological world and change the perspective of students with respect to biological systems. More specifically, we wanted students to understand that biological systems evolved to perform functions that are useful to the organism, and that all the components in a biological system contribute to a necessary function. Thus, a student, when observing the everyday biological world, would learn to see individual structures or features, and to ask what function that structure or feature accomplishes and why that is important to the organism. When students are practiced in this, they "learn to see the world through new eyes" – the world around them is no longer part of the background of their lives, but rather is now filled with potential solutions to challenging design problems [16].

Curriculum BID specific Activities

Several standard lessons and activities were used for teaching engineering, brainstorming for ideas, and as empathy building exercises for problem description. For example, we use SCAMPER, a semi-structured approach to ideation and improving ideas. The categories are, (S) Substitute, (C) Combine, (A) Adapt, (M) Modify/Magnify/Minimize, (P) Put to other uses, (E) Eliminate, and (R) Reverse/Rearrange [17]. In addition, we incorporate activities unique to BID, described here.

BID WOW: The first classroom activity shows an example of how nature may be used to inspire engineering, and ground students in the high-level concept of BID. A video of the BID Kingfisher-Shinkansen train example [18] is shown, and students are asked to react. These lead-off tasks or "BID WOW" (as expressing astonishment) activities, are intended to provide grounding instances of BID to help the student make the connection between the natural world and engineering design and to motivate them by demonstrating what is possible. They occur regularly throughout the course at the beginning of class to continuously reinforce the connection and are intended to create emotional engagement at the start of class.

Found Object Exercise: We ask students to go outside and explore nature, find a single biological “found object,” draw that object in detail, and consider the connection between the structures of the object and the function that structures performs. We found that asking them to interact with and draw the object allows them to see details they might otherwise miss, and to identify specific features of interest [14]. This exercise is meant to enhance the connection between students and the biological world around them, build and reinforce the connection between structure and function, and scaffold lessons for describing complex systems using Structure-Function-Mechanism (SFM), described later. We also provided videos of zoos and botanical gardens in case of limited opportunities to access to nature.

Lotus Effect Experience: The first two weeks of the curriculum, or the Launcher unit, is built around the problem of keeping surfaces clean and provides a quick and engaging overview of BID through a short design challenge motivating the need for BID and engineering as solutions [19]. After students first consider existing solutions to cleaning and ideate on their own solutions, they are introduced to the “Lotus Effect.” This refers to the self-cleaning, superhydrophobic properties of the lotus leaf, causing “water to bead up on the leaf’s surface and roll off [19, p. 3],” thus ridding itself of contaminants. Such nanoscale features are difficult to ground experientially, but the effect can be easily reproduced for students using Rustoleum’s NeverWet product, a spray that adds superhydrophobic technology to surfaces to protect them from elements such as water and dirt [20]. Upon learning about the lotus effect, students coat one half of a variety of surfaces in the NeverWet and test the interaction of those surfaces with fluids of varying viscosity, wetness, and staining properties, such as water, honey, mustard, and ketchup. Students are then asked to reconsider how they might change their design using this concept.

Structure-Function-Mechanism: All observable biological systems consist of a vast number of identifiable features that are often multifunctional, complex, and connected. Prior research cites the difficulty that novice students have in finding a point of focus for their descriptions. Novice descriptions are often a random-walk through the most striking structural features and little else. The SFM framework [21], [22], based on *Structure-Behavior-Function* or SBF [23], [24], [25], was developed to help students focus on specific biological features, and to describe them in ways useful for design thinking. Moore et al. summarize SBF as “a design ontology that describes how interactions among structural elements give rise to functions” [26, p. 2]. While we leave the SFM framework description to other publications, we provide several scaffolding activities to assist students with learning and applying the framework in class. For example, we apply the framework to objects like screws and nails, to help familiarize students with it, and ease them into this way of “mechanistic” thinking, which is notoriously difficult for novices.

Core Science Lessons: Our second design challenge is to design a lightweight container for food that keeps cold food cold and warm food warm. We undertake to explain thermodynamics fundamentals to students to help inform their design choices. These fundamentals are also critical for understand how biological systems manage heat and cold, which is required for students to be able to transfer these concepts from biology to human designs without falling prey to structural fixation [27], [28], [22], a.k.a. “hairy house problem.” We provide lessons in basic science, and guide students through a design experiment using these concepts (keeping an ice cube from melting) to provide a grounded experience for students to fall back on when trying to design their lunchboxes, and for use in understanding biological systems.

Study Context and Participants: Due to COVID-19, the curriculum testing in the classroom was delayed for multiple years. It was first pilot tested in two 9th grade engineering classrooms across two schools during Spring 2022. We recruited two high school engineering teachers. The teachers received two days of professional learning training, and on-going support through weekly online meetings. While one teacher taught engineering for three years in the same school (57% White students, 20% Hispanic, 16% black, and 5% other minority), the other participant was a first-year engineering teacher. However, the novice teacher was previously a biology teacher in the same school (37% White, 13% Hispanic, 13% Black, and 37% other minority). While there were some variations in terms of curriculum implementation, this paper only addresses students' preliminary results. Data was collected from four groups of students (*n*=12) enrolled in the engineering courses across two schools. Of the 12 students, 5 were female and 2 were white. The groups were a good representation of the overall classroom demographics.

Data Sources and Analysis: The study includes student data such as student artifacts and student focus groups. We utilized qualitative content analysis, which is a form of descriptive approach [3], [4] to analyze student data. Systematic analysis and interpretation of material is used to uncover the meaning and presence of text, messages, images, and transcriptions of dialogues [4]. Development of a rubric for measuring student learning is still on-going.

Preliminary results

Student groups enjoyed BID activities as they promoted students' exploration of biological systems. One student shared that activities were "fun, interesting, and good" and that the course was a "good class if you're interested in engineering." Another explained that "looking at nature to find ideas is good," but incorporating biology "gave more options and ideas" for project designs. Others mentioned that integrating biology and engineering helped them to "think and learn differently" and "better understand engineering." Furthermore, students saw activities as authentic opportunities for combining "learning engineering" within "real world contexts." For the final project, they designed and built a prototype of a food container for senior citizens, that maintained the temperature of hot and cold foods among other requirements. A student described it as "fun, [since we were] getting to make something that would actually be in the real world." Still, another remarked that "building, data processing, and…the overall project" helped them to "see what it would be like to be an engineer," which may have implications for interest beyond the course. Students from different groups, within and across schools, shared these sentiments.

BID integration allowed students to view nature differently, which some indicated they had not previously employed for their design solutions. All students expressed appreciation for recognizing connections between nature and objects around them. One student mentioned that learning and using biology in engineering was an "intriguing" way to "see a different aspect of engineering," while another referred to it as "intriguing and cool." Students at the other school also appreciated gaining a new perspective on nature through BID. One student expressed that "incorporating bioengineering in the brainstorming" enabled them to "see how animals use their natural characteristics to live." Moreover, students said they were better able to see nature-inspired objects around them, "on a regular basis" and that it was "cool" to know that there are "things that are all around you every day [that] are inspired by nature."

A couple of students acknowledged connections between BID integration and the design process, specifically the ideate phase. This was interesting, as making connections between BID and ideation was an important objective of the course. One student admitted that while the "biological concepts [were] not new…it made it easier to know that you can find ideas around you and not have to think of them yourself," thus implying a connection to the ideation phase of EDP. A different student shared that BID integration provided an "opportunity for students to use biology in a novel way as insight into engineering, and specifically the EDP," making an even further connection to the design process. Nevertheless, while some students mentioned BID activities that helped them during the "brainstorming phase" of the design process, they were unable to explain BID integration in their final design solutions, unless prompted by the teacher. This result is not uncommon for novice students in a semester-long K-12 engineering course.

Students across groups indicated that "prototype and test" was the most engaging stage of the EDP, since they got to test their designs. One student saw it as one of the most important stages, as it was "necessary for improving their product." When asked what they thought was the most "fun stage of the engineering design process," most students mentioned prototyping and its various aspects. Some students alluded to the fact that it "appealed to their learning style of being a hands-on learner," while others got "to see if the idea worked or ways to improve it." Several mentioned that "building and designing stuff" was the best part of the project, and that by learning the EDP they "could personally use the process to get things done." One student even mentioned that "prototyping was the highlight of working as a team." Yet, there were challenges, as a student cited that it was difficult to "prototyp[e] with limited materials" while another mentioned that they "couldn't do much with bubble wrap and cardboard." A student further explained that "there was not that much room to fit the actual container inside the lunch box since they had to "stuff it with bubble wrap for it to [maintain] the [required] temperature."

Students also shared some suggestions for improving the curriculum. Most concerned the worksheets, such as "make them less repetitive," and even "incorporate more biology [in tasks]." Others saw the worksheets as "[helpful], but slight changes in sketches didn't seem to make a difference," and that they were "[good to include], but not *as* many." In reference to the food container design challenge, a student wanted to build the prototype from the first design, then "see what they did wrong and refine it," rather than "refine it eight times before…building it." Similarly, another shared that, "the design process helped to get to [the] idea, and since [we] were already set on it [we] wanted to move forward on that idea rather than refine it." Still one student pointed that since "people learn different things, the [curriculum] is good as is." Indeed, most students seemed to have a positive view of the curriculum and they mostly agreed that it was a "good [course] overall."

Discussion

This research is novel in its focus on understanding high school students' experiences with the integration of BID in engineering and has important implications for diversifying engineering in K-12 education. Important lessons were learned regarding students' experiences. It was evident in the data that students liked the BID activities. Their final design included aspects of bio-inspired design. However, we did not see much of an alignment between students' nature investigation activities and their final design. This may highlight implications about the curriculum scaffolding regarding connecting BID with EDP. It could also have been impacted by teachers' curriculum implementation variations and professional development. During 2022-2023 school year, we are fully implementing the curriculum in three schools. All the teachers went through a more extensive training, and the curriculum was updated after the pilot. The future results will help us to further understand students' learning experiences.

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