Creating Biologically Inspired Design Units for High School Engineering Courses

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***Abstract*—This innovative practice work in progress paper presents the Biologically Inspired Design for Engineering Education (BIRDEE) project, to create socially relevant, accessible, highly-contextualized biologically inspired design experiences that can be disseminated to high school audiences engineering audiences in Georgia and nationally. Curriculum units are 6-10 weeks in duration and will meet many standards for high school engineering courses in Georgia. There will be three curriculum units (one for each engineering course in the 3-course pathway), each building skills in engineering design and specific skills for BID. Currently in its second year, BIRDEE has developed its first unit of curriculum and has hosted its first professional development with 4 pilot teachers in the summer of 2020. The BIRDEE curriculum situates challenges within socially relevant contexts and provides cutting-edge biological scenarios to ignite creative and humanistic engineering experiences to 1) drive greater engagement in engineering, particularly among women, 2) improve student engineering skills, especially problem definition and ideation skills, and 3) increase students awareness of the connection and impacts between the engineered and living worlds.**

This paper describes the motivation for the BIRDEE project, the learning goals for the curriculum, and a description of the first unit. We provide reflections and feedback from teacher work and focus groups during our summer professional development and highlight the challenges associated with building BID competency across biology and engineering to equip teachers with the skills they need to teach the BIRDEE units. These lessons can be applied to teaching BID more broadly, as its multidisciplinary nature creates challenges (and opportunities) for teaching and learning engineering design.

Keywords—K-12, engineering curriculum, biology, diversity, women

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I. Introduction

To meet 21st century global economic demands for innovation and design, we must increase the pipeline of STEM students from a more diverse cross-section of the population. In the past two decades, K-12 engineering has been growing. Integrating engineering in pre-college curricula provides opportunities for students to better learn science and math [1], promotes understanding of engineering design [2], increases students' technology literacy, and raises awareness about what engineering as a profession and career is [3]. Thus, recent efforts have been made to increase accessibility of engineering for diverse students by developing appropriate integrated engineering opportunities for them.

However, counter to this goal is the research that shows high school females have historically lacked interest and opportunity in engineering [4]. Most engineering disciplines attract female students at a rate of 20%, while bioengineering and biomedical engineering achieve 59% [5], and biology 60% nationally [6]. We hypothesize that the social relevance and measurable impact of biomedical engineering, along with compelling biology content, attract more female students to these disciplines [7]. Based on these data, the inclusion of biologically inspired design (BID) in high school engineering courses may attract and retain more women students, while building knowledge of the engineering design process and enhancing design creativity.

II. Project Overview

A. What is Biologically Inspired Design?

Biologically inspired design (BID) uses biological analogies to enhance the creativity, innovation, and sustainability of engineered products. Famously, George de Mestral invented Velcro through the careful observation of the hook-and-loop design of burs as they stuck to the fur of his dog [8, 9]. The

Wright brothers, by observing soaring buzzards, invented wing deformation features to assist with aircraft maneuvering. Broadly speaking, BID leverages the wisdom of 3.8 billion years of evolution in nature to develop more sustainable solutions to humanity's design problems [10, 11]

B. *Project Components*

Our vision for this *Biologically Inspired Design for Engineering Education* (BIRDEE) project is to create socially relevant and accessible biologically inspired design experiences that can be disseminated to high school audiences in Georgia and nationally. BIRDEE will create, implement, and evaluate its standards-based curriculum in high school engineering classes. BIRDEE will situate design challenges within socially and sustainability relevant contexts and will provide biological sources of inspiration to ignite students passion for innovation. These highly-contextualized engineering experiences will 1) drive greater engagement in engineering, particularly among females, 2) improve student engineering skills, especially problem definition and ideation skills, and 3) increase students awareness of the connection and impacts between the engineered and living worlds.

The project has 3 primary goals:

- Develop high school engineering curriculum units for the three-course engineering sequence in Georgia high schools.
- Implement the curriculum in partner schools, applying Design-Based Implementation Research [12] best practices to analyze and address issues related to implementing BID in existing engineering courses in typical public schools.
- Assess the effects of the BID curriculum units on: student learning of the engineering design process; student engagement in engineering; student design self-efficacy and intent to persist in engineering; and student and teacher attitude about sustainability and the biological world.

This paper is focused on the curriculum development goal. We present the learning objectives of the unit, a description of the unit with its designated activities, and some of the assessments.

III. BIRDEE CURRICULUM

BIRDEE is developing and implementing three engineering design curricular units, one for each course in the three-course Georgia engineering sequence: *Foundations of Engineering, Engineering Concepts and Engineering Applications*. Units will be 8-12 weeks long, with later units in the course progression being longer to account for the greater complexity of the design task and learning goals.

A. *Unit Progression*

The three consecutive units are designed to build upon each other. However, it cannot be assumed that all students will take all the units or even the prerequisite units; therefore, they are all designed to stand alone. The first unit focuses on helping students learn the engineering design process, with considerations for BID, with emphasis on problem formulation and problem-solution co-evolution [13]. They are asked to research a particular given problem space and are guided to biological solutions that may enhance their design creativity.

In the second unit, students start with biology first before considering its applications to possible engineering problems. This is counter to how design is normally taught; but historically and in practice, this is how most BID has happened in practice [14]. Specifically, students will explore elephant trunks and learn about BID research taking place around how elephants can grasp objects and elongate their trunks. Students are guided to integrate what they learned from elephant biological systems to create novel elephant-inspired robotic systems. They will engage in design challenges around a suction-based robot that can pick up small objects and a hydraulic robot that can be controlled using water in syringes. Students will modify these robots to move certain objects effectively.

In unit 3, students will engage in an open-ended engineering design problem, where they are asked to use BID independently to solve the problem and design a solution. To create a capstone design experience, students will be asked to engage in problem finding (i.e. an invention process), giving students some autonomy over their problem domain. Research on invention education in formal learning settings indicates that teachers believe invention fosters 21st century skills (e.g., creativity and teamwork) and students' ability to learn from failure, and in Georgia, the state invention competition attracts around 50% women [15]. Unit 3 will build on the invention process and augment students' creativity through guided biological inspiration.

B. *Engineering Design Process*

The BIRDEE curriculum will integrate BID into the Engineering Design Process (EDP) by leveraging analogical design tools that facilitate transferring biological design principles to engineering challenges. There is evidence that problem definition, problem understanding. and design ideation are often not taught very well in K-12 engineering courses [16]. With these steps being the most human-centered, the tendency to rush to prototyping rather than practice these early steps could impact engagement and personal connection with

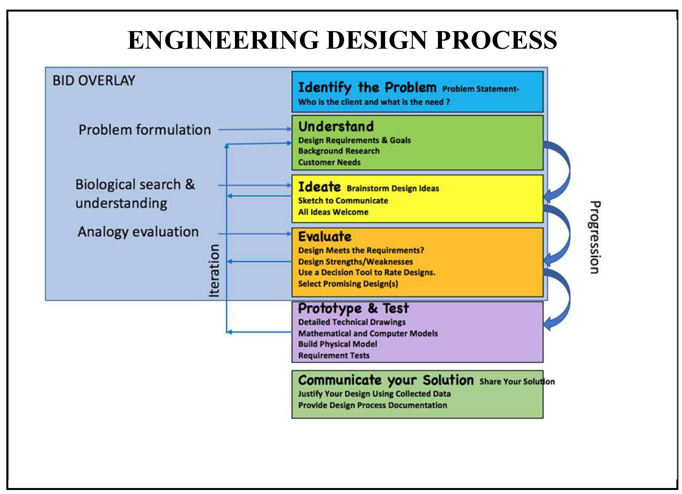

Fig. 1. Engineering design process with BID augmentation

engineering. Likewise, this could lead to fixation, a well-known problem in design[17, 18]. Mentzner, et al[19] report that high school engineering students understand their problems poorly and often fixate on a single solution.

The BIRDEE curriculum will address these early steps of the engineering design process. Existing tools for undergraduate courses will be modified to scaffold the key engineering design skills of problem understanding and design ideation. Figure 1 illustrates the engineering design process when augmented with BID.

C. *Student Understandings for BID*

The curriculum team engaged in a backward design approach, defining desired student enduring understandings in order to develop a meaningful set of curricular activities [20]. While many of the student understandings were centered on general engineering design process learning, some of the more challenging understandings to define were BID-specific. Some of the BID understandings that are guiding development of the three units are:

- Analogies allow engineers and designers to develop solutions to problems by leveraging existing solutions to other problems that may share certain commonalities.
- To design more sustainable products, engineers change their perspective by examining the interface between nature and their created product.
- To find inspiration from nature and enhance design creativity, engineers use functional decomposition of problems to reveal functional similarities between human-scale problems and biological solutions. These commonalities provide a method to search for, find, and apply biology to the design problem.
- To improve/expand the number of solution pathways, engineers use biological sources for inspiration. This enhances the variety and novelty of designs produced.

D. *Unit 1 Description*

Unit 1 is an 8-week curriculum designed for the Foundations of Engineering course, a first-year course generally taken by freshmen and sophomores in high school. The unit is designed to meet some of the state standards set forth by the state of Georgia, but because it is not a full year curriculum, it does not accomplish all of the standards for the course. It is our hope that this course would be implemented early on in the year, perhaps not as the very first project, but early enough that some of the skills and approaches used by the teachers and students will carry forward to other projects and challenges assigned during the remainder of the school year.

The first two weeks of the curriculum is called the 'launcher,' which was designed to give a quick overview of BID in a highly engaging short design challenge that motivates the need for some of the BID and engineering tools. The launcher was designed to help students understand the basics of the engineering design process and the power of biology as a source of inspiration focused around 'The Lotus Effect' phenomenon.

TABLE 1. Unit 1 Overview

	Key Activities
Weeks 1&2	Launcher- The Lotus Effect mini design challenge
Week 3	Introduce the Challenge Product Dissection
Week 4	Structure Function Mechanism, biology
Week 5	Structure Function Mechanism, engineering Heat Transfer Experiment
Week 6	Concept Ideation & Evaluation Low-Fidelity Prototypes
Week 7	Prototyping & Iteration
Week 8	Communicate & Present Solutions

In this launcher, the curriculum starts by having students think about problems related to things getting dirty or stained. Students research existing solutions to this problem and ideate new possible solutions. Then a biological solution, in this case the lotus leaf, is introduced. The lotus leaf exhibits an extreme hydrophobic behavior, dubbed 'The Lotus Effect', though other fauna such as elephant ear plants also exhibit the effect. The hydrophobic effect causes water to bead up on the leaf's surface and roll off, taking dirt and other contaminants with it. This is why lotus leaves look clean in an otherwise murky pond or lake. In the unit, students research the science behind the lotus effect (at a general level) and do a hands-on activity using an off-the-shelf product that is based on the lotus effect and provides a waterproofing coating to materials. Students then ideate new possible solutions inspired by this biological solution.

The remaining six weeks of unit 1 provide a more detailed exploration and design challenge focused on 'thermal regulation'. In week 3, a design challenge is provided regarding senior meal delivery, asking students to ideate lunch boxes that can keep warm food warm and cold food cold. A product dissection activity allows students to analyze existing lunch boxes and think about how they act as insulators and as transportation devices.

In week 4, we introduce 'structure, function, and mechanism (SFM)' as a way to analyze systems, both engineered and biological [21]. In this week, we focus on biology. The purpose of this analysis is to observe nature in a systematic way so that it can be mapped more readily to engineering situations. At a high level, the structure is typically what is visible to the observer, e.g., polar bear fur. The function is what that structure accomplishes, in this case, insulation. The mechanism is the hardest to uncover, but most useful in terms of transfer. In this example, the mechanism has to do with air pockets that reduce the heat transfer from the bear's skin to the air. In this activity, students examine SFM for different thermoregulation systems. Nature examples such as polar bear fur and penguins huddling are provided so that students can grasp a variety of mechanisms found in nature.

In week 5, we repeat SFM, but we move to the engineered world, this time using a jar experiment. This jar experiment is designed to show how different insulative materials wrapped around the jar change the thermal characteristics of the system (ice melting inside the jar). Students learn how to use electric temperature sensors and how to plot/graph data recorded by those sensors and to interpret the data.

In weeks 6 &7, students start ideating their own solutions for lunch boxes using what they have learned in the previous weeks. They understand what existing lunch boxes look like, how nature accomplishes thermal regulation, and how different common materials can change thermal behaviors. Students will build lunch box prototypes and test them. In week 8, students present their work and provide feedback to each other.

E. Formative & Summative Assessment

We will evaluate and assess students' engagement and learning in BID and engineering design using formative and summative assessments. Throughout the unit (formatively), we will use several team-based activities such as creating posters, presentations, conceptual design sheets, and individualized activities where students are guided to present their ideas and share their BID understanding and reflections. They will also engage in self-assessments and peer-evaluations. Additionally, students will be logging their design activities in an electronic tool developed specially to capture engineering design engagement. At the end of the unit (summatively), student teams will give presentations in which they share their engineering design process, artifacts and teamwork. The design logs will be assessed using a rubric we created that integrates engineering design into BID based on [16].

IV. Conclusion & Future Work

This paper describes some of the progress-to-date on the development of BID units for high school engineering courses. Unit 1 is described briefly, while Units 2 & 3 are still in development. Future work will present the full list of student understandings, the full suite of curriculum, and a mapping showing how curricular activities build understandings across the units. Due to COVID-19, no classroom implementation has yet taken place; implementation will be necessary for feedback and to answer the project's research questions. As soon as the implementation is permitted by school districts, we will collect data to capture ways teachers and students engage in different curricular activities. We will also specifically focus on experiences of students from historically underrepresented group in engineering. The research findings will be important for modifying our own curriculum, and can also inform other curriculum developers, educators and researchers as BID is gaining attention.

Overall, we believe the BID and the accompanying tools and frameworks such as SFM may be transformative in how students see the engineered and natural worlds. This is based on feedback and experience from existing undergraduate courses offered at Georgia Tech and the experience of the project team.

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