International Journal of Engineering Education Vol. 40, No. 4, pp. 715–732, 2024
Printed in Great Britain

0949-149X/91 $3.00+0.00

Exploring High School Engineering Students' Integration of Biological Concepts in the Engineering Design Process*

ABEERA P. REHMAT and MELTEM ALEMDAR
Georgia Institute of Technology, Center for Education Integrating Science, Mathematics, and Computing (CEISMC), 505 10th St. NW, Atlanta 30332, USA. E-mail: arehmat3@gatech.edu; meltem.alemdar@ceismc.gatech.edu

MICHAEL E. HELMS
Georgia Institute of Technology, The George W. Woodruff School of Mechanical Engineering, 801 Ferst Dr, Atlanta, GA 30332, USA. E-mail: michael.helms@me.gatech.edu

ROXANNE MOORE
Georgia Institute of Technology, Center for Education Integrating Science, Mathematics, and Computing (CEISMC), 505 10th St. NW, Atlanta 30332, USA. E-mail: Roxanne.moore@gatech.edu

MARC J. WEISSBURG
Georgia Institute of Technology, School of Biological Sciences, 310 Ferst Drive, Atlanta, GA, 30332, USA.
E-mail: marc.weissburg@biology.gatech.edu

Biologically inspired design (BID) in engineering is a systematic approach that employs analogies from biological creatures to develop solutions for engineering problems. BID is becoming increasingly prevalent in pre-college education as it facilitates students' understanding of how natural systems and features can inspire the design of systems to solve societal problems. This qualitative descriptive study investigated high school students' (n = 53) use of biological systems, processes, and concepts covered in the BID-integrated engineering-focused curriculum in the engineering design process (EDP) to develop a solution to the engineering problem. The EDP is an iterative method employed by engineers for effective problem-solving which students employed to create a better food delivery system for senior citizens. Several data sources were used to examine students' application of BID-integrated EDP, including classroom observation field notes, final design presentations, and semi-structured focus groups. Qualitative thematic analysis revealed four major themes: *criteria/constraints, integration of biologically inspired design in the engineering design process, decision-making, and internalizing of structure, function, and mechanism*, demonstrating that students engaged in the engineering design process holistically and iteratively and incorporated features of biological systems in their design solutions.

Keywords: engineering education; biologically inspired design; K-12 education; design-based learning

1. Introduction

In our evolving society, the proficiency of future engineers in navigating "multidisciplinary, interdisciplinary, and transdisciplinary environments" [1] (p. 2) has become an essential competency. As a result, biologically inspired design has emerged as a distinctive academic discipline in both undergraduate and graduate education. This discipline is purposely designed to equip students with the skills needed to solve problems that transcend disciplinary boundaries, fostering their ability to "transfer knowledge and collaborate across technical and non-technical boundaries" [1, p. 3]. Biologically inspired design (BID) is a method for using principles from nature to solve engineering design challenges. Stone et al. [2] emphasized that bio-inspired design aims to "systematically mine biological knowledge to solve existing design problems" (p. 2). It is engaging, novel, and leverages sustainable technology produced by over three billion years of adaptation [3]. BID is part of a field of design strategies that draw inspiration from biology, including biomimetics, bio-design, bio-utilization, biomimicry, and bionics [4]. Each of these design strategies has a slightly different definition. However, all these disciplines turn to biology for innovative solution pathways, presenting unique opportunities to amplify creativity, novelty, and sustainability in design solutions [5–8]. The inclusion of BID in both undergraduate and graduate education has demonstrated many benefits, such as boosting students' interest in engineering, fostering knowledge transfers across domains, and supporting novel ideas [8], leading to innovation and efficacy [5–8].

Moreover, BID may also help to reduce design fixation, defined by Jansson & Smith as "a blind adherence to a set of ideas or concepts" [9, p. 3], because design-by-analogy techniques have been shown to mitigate design fixation [10]. While BID has a presence in higher education, systematic integration of BID in pre-college curricula is still deficient [1, 11–13]. Considering the advantages

* Accepted 19 March 2024.

observed of integrating BID concepts into higher education, there is promise in introducing pre-college students to multidisciplinary learning in BID through integrative BID design curricula. Incorporating BID into K-12 education has the potential to offer a holistic approach that enhances creativity, problem-solving skills, and interdisciplinary knowledge while fostering an early appreciation for sustainability and environmental consciousness. Nonetheless, BID integration must be coupled with student-centered pedagogy, such as design-based learning that fosters students' engagement in generating innovative BID-inspired artifacts, systems, and solutions [12], which are fundamental to engineering [1].

In 2019, NSF funded a DRK-12 project entitled *BIRDEE* (Biologically Inspired Design in Engineering Education) to create socially relevant, accessible, and highly contextualized high school engineering curricula focusing on bio-inspired design. A seven-week curriculum was designed to integrate bio-inspired design into the existing engineering design process (EDP) frameworks. This was achieved by employing analogical design tools specifically designed to facilitate the identification and transfer of biological strategies to various design challenges [11–14]. The purpose of this study is to investigate how high school students' integrative use of analogical design tools for BID, when integrated with an existing EDP, influences their ability to solve design challenges.

1.1 Literature Review

1.1.1 Biologically Inspired Design in Pre-college Engineering

Biologically inspired design involves applying biological organisms and systems as inspiration for designing solutions to engineering challenges [5]. In recent years, BID has gained momentum in pre-college education as a means for students to engage in creative and interactive problem-solving [1]. This integration also aligns with Next Generation Science (NGSS) and engineering standards, emphasizing structure and function, which are referenced as both cross-cutting concepts and disciplinary core ideas [15]. Further, BID's interdisciplinary nature makes it appealing to underrepresented students in engineering, fostering practical problem-solving skills [1, 16, 17].

For instance, a study by Bernstein et al. [18] engaged students in a BID curriculum and encouraged them to model biological mechanisms for robot design. This multidisciplinary approach supported learning across disciplines, cultivating higher-order thinking [18]. Additionally, the integration of biology with engineering courses has shown promise in attracting more women to STEM fields [19]. Research has shown that while most engineering programs only attract 20% of females, engineering programs adjacent to biology, such as biomedical engineering and bioengineering, are 59% female [19]. Similarly, biology programs encompass 60% of the female population [20]. Consequently, by infusing K-12 engineering courses with biology, more females may express interest in engineering courses and programs [21].

BID also influences students' perceptions of nature's importance as a source of inspiration for their design solutions. Studies suggest that through participating in BID activities, students' beliefs (i.e., interests and attitudes about biology) were reinforced about nature [1, 22]. Moreover, students felt that nature itself could serve as inspiration for design and foster feelings of creativity [1, 22]. Laut et al. [23] found that BID-integrated engineering design challenges enhanced students' understanding of the interaction between engineering and nature, fostering positive views of engineering. The findings revealed that BID integration in projects encouraged students to think about how nature can be applied to solve modern-day engineering problems [23].

These studies collectively underscore the potential and the positive impact of BID in pre-college engineering education [1, 16, 17, 22–24]. The hands-on and collaborative nature of BID activities can nurture students' use of both engineering and biological principles to solve an engineering design problem [12–14, 18]. Hence, it is imperative to design curricula for pre-college engineering education that introduce students to BID learning through engagement in the engineering design process (EDP).

1.1.2 Engineering Design Process

The utilization of the engineering design process (EDP) is increasingly mainstream in pre-college education. The EDP is employed in K-12 education as a tool to support engineering thinking and decision-making and prevent oversight when solving engineering problems [25]. The EDP is an iterative method employed by engineers for effective problem-solving. It involves a sequence of steps, including problem identification, understanding, ideation, evaluation, prototyping, testing, and sharing the solution [26–28]. Given that design problems are often characterized as "ill-defined" or sometimes "wicked" [29, 30] and "have a multitude of satisfactory solutions" [31, p. 15], the EDP serves as a valuable tool for exploring various ways to scope a problem. This involves defining the problem and gathering essential information [32]. The open-ended nature of the EDP helps generate multiple solutions to a problem as well as guide the analysis of possible solutions, ultimately leading to discovering the most optimal solution [33]. In K-12 classrooms, the EPD enables students to learn from failure and solve problems from a more open-ended, holistic lens [34].

The EDP has been employed widely across formal and informal learning environments for STEM and science teaching and learning in pre-college education [13, 24, 28, 35]. However, the specific EDP integrated across these settings differs due to grade-specific standards, curriculum, and teachers' experiences and backgrounds [35–38]. Many studies have highlighted that students and teachers at different age levels focus on different parts of the design process [35–37]. For example, idea generation was found to be central to elementary students' engagement in engineering design [36, 37]. In contrast, predictive analysis and testing/revising were the factors that mostly influenced high school students' design thinking [38].

Similarly, high school engineering and technology teachers tend to focus on prototype construction and redesign [35]. Furthermore, there is also evidence that rethinking and redesigning how problem definition, problem understanding, and design ideation are taught in K-12 engineering courses could further impact engagement and personal connection [1]. Students who spend more time on problem definition and understanding develop multiple solutions to problems and become creative with idea generation [39]. Idea generation ability is a crucial element of engineering design that pushes students to be innovative. One of the hypotheses in our curriculum design investigated the potential influence of BID integration on students' understanding and application of EDP within an engineering class. In other words, our study aim was to explore how a curriculum rooted in BID affects students' use of BID within the EDP stages, such as problem identification, understanding, and ideation to solve the engineering design problem.

1.1.3 Biologically Inspired Design Integrated Engineering Design

Biologically inspired design (BID) is fundamentally a design-by-analogy technique that uses biological analogies to inspire solutions to design problems [7, 40]. Classic design-by-analogy follows a process of design problem formulation solution identification wherein potential analogies are identified, mapped, and evaluated, and cross-domain analogies are understood in the context of the existing domain. Then, the relevant aspects of the analogy are transferred to the design problem [41–43].

Within biologically inspired design, there are numerous methodologies and tools for practicing, teaching, and learning BID [4], all of which contain each of the four classic defining characteristic aspects of design-by-analogy at various levels of granularity. Interestingly, BID methodologies and processes can be characterized as problem-driven or solution-driven [44, 45]. Problem-driven BID starts with a design problem, and then biological analogs are sought out to aid in developing an engineered solution [4, 45]. Whereas solution-driven BID begins with a compelling biological system or mechanism and then looks for engineering design applications [11, 45], the proverbial hammer in search of a nail. While problem-driven BID mirrors the EDP closely, solution-driven BID turns classic design-by-analogy on its head by first starting with a solution and then looking for an analogous problem to solve. Thus, the problem-driven method would seem preferred for introductory courses where both EDP and BID are integrated.

As both the EDP and classic design-by-analogy methods in BID begin with problem formulation, and because design-by-analogy relies on problem formulation to support the search and evaluation steps, emphasis on problem formulation and corresponding support tools, such as the 4-box method [46] is needed both to scaffold BID and to support and reinforce on this step in the EDP, an aspect which is otherwise frequently neglected [35, 38]. Moreover, because the understanding of complex biological systems is required to evaluate the fitness of the analogy to the problem, formal complex system modeling techniques, such as function-behavior-structure (FBS) [47], structure-behavior-function (SBF) [48, 49] and structure-function-mechanism (SFM) [39] may be integrated into the curriculum to scaffold evaluation and transfer. These tools are applicable across both traditional design processes and BID, minimizing the need for specialized techniques that might otherwise dilute engineering learning. There are many ways to effectively integrate BID in engineering design to support learning as documented in the literature [1, 2, 17, 18, 24, 51]. However, to encourage students' engagement in learning and enhance problem-solving, it is imperative that the context is socially relevant and the learning process is student-centric [24, 50, 51]. Further, the learning environment should facilitate collaboration, students' content learning, and creative processes. Design-based learning (DBL) is an instructional method that emphasizes the "planning and design of activities resembling authentic engineering settings" [50, p.718]. In a DBL learning environment, students engage in cognitive thinking processes as they engage in the iterative EDP [50].

1.2 *Theoretical Framework (Design-Based Learning)*

In this research study, student learning and engagement in the curriculum are grounded in the design-based learning (DBL) framework [24, 50]. Design-based learning is a constructivist approach to teaching and learning that combines the qualities of project-based learning and problem-solving through students' creative design solutions [51]. DBL is an inquiry-based form of learning or pedagogy that supports the integration of design thinking and EDP. It empowers students to construct scientific understanding and real-world problem-solving skills by engaging them in designing artifacts or systems that tackle real-life problems [50]. Through such engagement, students learn content as they collaborate to find innovative solutions and develop prototype models or artifacts for a solution, stimulating ingenuity [24].

Learning in a DBL environment is collaborative [54], allowing learners to actively construct knowledge rather than receiving information passively [52]. Such social spaces allow students to share, evaluate ideas, and co-construct knowledge [54], cultivating communication and collaboration skills for deeper learning [53]. In DBL environments, students are often required to become "experts" in a specific area by "establishing goals and constraints using representational approaches, idea development, and prototype construction for design projects" [53, p. 2]. This encourages active engagement via group work and stimulates innovation while cultivating cognitive and social abilities [52]. However, appropriate facilitator scaffolds are necessary for DBL to be a productive context for student learning [54]. Scaffolding maximizes the affordances of DBL for fostering students' knowledge construction, metacognition skills, and scientific reasoning [54]. For example, in this study, the teacher facilitated the learning by asking appropriate questions to help students notice and connect knowledge from multiple disciplines (e.g., biology, engineering) to develop a design solution [55, 56]. Scaffolding was also provided through multiple activities embedded within the unit to facilitate students' understanding of the core concepts (e.g., structure, function, mechanism) necessary for the design solution. This stimulated students' inventive thinking by focusing their attention on the main design issues and allowed them to make connections between various design stages [54].

DBL encouraged students to experience the construction of cognitive concepts as a result of their engagement in the BID-integrated design challenge throughout the seven weeks. As students collaborated to understand and create solutions, they engaged in complex and interwoven processes of inquiry and design, supporting transdisciplinary learning and engagement in BID [24]. Furthermore, the BID-focused design challenges afforded via DBL provided a logical framework that encouraged students to engage in interdisciplinary work and creative problem-solving [3]. The BID-focused engineering problems promoted students' engagement in the iterative EDP, including analyzing, abstracting, and synthesizing knowledge to arrive at innovative solutions by integrating knowledge of biological systems and engineering core ideas to develop a solution [24, 50]. Zhang et al. [51] assert that to foster DBL, the learning activity should be "open-ended, followed by a design process, and involve multidisciplinary knowledge and skills" (p. 853). This allows individuals to be inventive and initiate the learning process in accordance with their "preferences, learning styles, and various skills" [52, p. 23]. Although DBL emphasizes the importance of producing or engaging in designing activities for learning, the design process also offers a valuable learning environment for students [50]. In essence, DBL values the learning process and its outputs or products [53].

Design-based learning environments have been incorporated in many disciplines, including those that are traditionally associated with design (e.g., art, architecture, engineering, interior design, graphic design), as well as disciplines not considered to be design-related (science, technology, business, humanities) [57]. DBL has also been utilized across pre-college education [58–62]. In research, DBL has demonstrated positive learning outcomes, such as improving students' systems thinking, academic achievement, and collaborative skills [62]. Doppelt et al. [52] examined students' engagement and achievement as a result of engaging in the DBL and showed that DBL improved students' "desire to learn, enhanced students' success in science class, and increased students' interest in science topics" [52, p. 35]. Additionally, students were more engaged in DBL, which fostered learning and enabled them to explain scientific concepts [52]. Fried et al. [63] investigated the effects of a DBL on students' ability to apply biological concepts to societal benefits without compromising structure–function (S-F) understanding. The authors discovered a strong positive link between students' learning within a DBL context and how likely they were to report how S-F knowledge could be applied to benefit society [63]. Azizan et al. [53] explored the experience of science undergraduate students after one semester of participating in online DBL. The study revealed that online DBL enhanced creativity and encouraged students to think outside the box. These studies demonstrate the positive student learning outcomes as a result of their engagement in DBL, consequently making it an appropriate framework to explore students' integration of BID within EDP.

2. Methods

2.1 Purpose and Research Question

Students in this study participated in a seven-week BID-focused engineering curriculum. It was designed to introduce students to the EDP and BID as a method to enhance creativity and sustainability, providing rich data on students' engagement and use of BID in an engineering context that promoted students' engagement in DBL. This study aims to contribute to an understanding of the inclusion of BID in engineering education. The integration of BID in a high school engineering course is intended to benefit students' understanding of how life's systems and features can inspire the design of systems and products that solve human problems. Further, it broadens students' perceptions of engineering and motivates them with new ideas while stressing problem understanding, engineering design, and systems thinking. Specifically, in this study, we address the following research question: *To what extent were students able to integrate BID within the engineering design process to solve the engineering design challenge?*

2.2 Research Design

This research employed a qualitative descriptive [64] design to investigate how students use biological systems, processes, and concepts covered in the BID-integrated engineering-focused curriculum in the engineering design process to design a solution to the engineering problem. Qualitative descriptive studies draw from the general tenets of naturalistic inquiry, which allows investigations of a phenomenon in its natural state. This methodology is a good fit for studies "when straight descriptions of phenomena are desired" [64, p. 339]. Further, it is advantageous when the research seeks to address 'why' and 'how' questions holistically within a specific context or situation [64]. The target phenomenon in this study is student groups' integration of BID in the EDP to solve the engineering problem. Thus, the qualitative descriptive design allowed for a deeper understanding of students' engagement and application of BID-integrated EDP.

2.3 Setting and Participants

This research study was conducted in a ninth-grade engineering classroom within a southeastern metropolitan school district located in the United States. The school was a STEM-focused high school with a diverse student community, where 37% were White, Asian (37%), Black (13%), Hispanic (8%), and Multiracial (5%). The student data was collected from the classroom of an engineering teacher who was formally certified to teach 6–12 engineering and science [12]. The teacher was a second-year engineering teacher with 20 years of prior experience teaching high school science, specifically biology. The teacher had previous experience implementing the BIIDEE curriculum in his first year of teaching engineering during the pilot study [12]. This was followed by his participation in an in-depth summer professional development related to BID integration in engineering. He taught one section of the introductory "Foundations in Engineering" course, which was divided into three block sections, all with the same curriculum and lesson plans. Each block period was approximately 90 minutes long. The curriculum implementation was seven weeks long, and an additional three days were allocated for student group presentations [12].

Although all the block sections were observed, data was collected from six teams in each block section (n = 53; 18 teams total), which comprised three to four students within each team throughout the seven-week unit. To minimize gaps in data due to common causes such as absenteeism, student transfer, and failure to follow procedure, especially considering the recency of return-to-normalcy after COVID, the teams were selected based on the teacher's recommendation since the members were particularly communicative with each other and provided both parental and student consent. Also, due to COVID restrictions and difficulty with teacher retention and recruitment, the participating teacher, who was recruited in the Fall of 2021, did not participate in professional learning during the summer of 2021. Thus, a pilot study was conducted in the Spring of 2022, which enabled the teacher to pilot curriculum implementation [13]. Further, the pilot study helped refine the curriculum and research protocols. This study (field study) was conducted with ninth graders entering in the fall of 2022. The teams were diverse in regard to race and gender (See Table 1 for the team's demographic). The authors acknowledge that this selection criterion likely favored higher-performing teams, and results may not generalize across the class population.

2.4 Context: BID-focused Engineering Curriculum

Students in this study participated in the design-based BID-focused engineering unit, BIRDEE unit 1 [12]. The unit was designed to introduce students to both the EDP and BID. For many students, this was their first exposure to the formal EDP, and for most students, it was their first exposure to BID.

Table 1. Participating team's demographic information

Category	Subgroup	Frequency (N)	Percentage (%)
Gender	Male	25	47%
	Female	28	53%
	Total	**53**	**100%**
Race	White	15	28%
	Black/African American	9	17%
	Asian	25	47%
	Native American	1	2%
	Hispanic	1	2%
	Other/Mixed	2	4%

Because state and national standards are focused on student learning of the EDP in the high school engineering course, the curriculum emphasized EDP learning and structure while positioning an integrated BID within that context.

The unit utilized design challenges that were situated within socially relevant contexts to facilitate the learning of core concepts and skills, in which students iteratively developed a solution over multiple weeks [12, 24]. Students also learned about biological systems and biological processes relevant to their problems. As students engaged in problem-solving through the EDP, they integrated BID into the EDP (See Table 2) by leveraging analogical design tools (i.e., structure, function, mechanism analysis) that aided with facilitating a transfer of biological strategies to the design challenge, while also supporting key EDP processes (e.g., complex system understanding) [39]. These tools scaffolded the key engineering design skills of problem understanding and design ideation. Further, because of the emphasis of design-by-analogy on understanding the design problem, the unit focused on early problem-understanding steps, which were also anticipated to increase the connection to human-centered aspects of design and enable better learning outcomes in the engineering design process [3].

The BIRDEE unit 1 was divided into two parts: the *launcher* and the *design challenge*. The unit commenced with the launcher, introducing students to the "lotus effect", in which students model the water-repellent properties of lotus leaves using a product called NeverWet [12, 13, 24]. This product is investigated in the context of the problem of how to keep shoes clean, as NeverWet can be applied directly to surfaces and creates a repellent and protective coating [12, 13]. Students learn about the scientific basis for these properties and explore the engineering applications of the biologically inspired product. In the launcher, students are first introduced to the EDP and the BID concept. Each step of the EDP is modeled through the design challenge to solve the problem of dirty shoes [12, 13, 24].

In the formal design challenge, students are introduced to the problem via a client memo from a company (EatEZ) requesting them to design a better food delivery system (Lunch boxes) for senior citizens (See Fig. 1).

As students engage in the design challenge, they are introduced to biological concepts of thermoregulation and various examples of animals that have evolved complex and effective methods for regulating their body temperature (polar bear fur,

Table 2. Application of the BID-integrated EDP

Engineering Design Process	Description
Identify the Problem	• Define a need and a user • Create a problem statement
Understand	• Identify the design requirement using the 4-box method • Conduct market research of current available solutions, including investigation of biological solutions
Ideate	• Brainstorm several ideas • Design sketches and descriptions of possible solutions • **Apply biological strategies and bio-inspired design concepts**
Evaluate	• Compare design strengths and weaknesses • Cross check with design requirements
Protype & Test	• Create detailed drawings and physical models • Complete required testing
Communicate	• Share design solution • Justify design solution • Provide design process documentation

EatEZ

To: Engineering Students
From: EatEZ Organization
Subject: Request for Design Ideas

Dear Engineering Student Designers,

EatEZ organization is a non-profit organization that aims to improve food accessibility to seniors. As they get older, seniors experience physical declines or financial hardships that reduce their independence and result in millions of seniors being hungry. In order to address these issues, our organization supports seniors by delivering high-quality, nutritious meals to them on a daily basis. We have many volunteers across different ages who help us with food delivery.

Current method of food delivery: Every volunteer has to put all the warm boxes of food in one large, insulated container and all the boxes of cold meals in a different one. When they get to each senior, they give one warm meal box and one cold meal box to the senior. Additionally, some seniors have specific dietary restrictions, so we have customized food boxes. They are labeled with the seniors' names. See the pictures below.

Problem: Based on our recent survey, both our volunteers and our seniors seem to be dissatisfied with the current method of food delivery.

1. Food temperature: On average, seniors eat their food 1-2 hours after the delivery. This makes the food either too cold or too warm for them.
2. Ease of use: Having the customized food makes the food delivery hard because the volunteers have to find the right box for the individuals in the big container they have.

Therefore, our organization decided to use individualized insulated bags for each senior to maintain the food's temperature.

Request: The organization is seeking engineering students to design a handy meal delivery insulated box/bag that keeps one container warm and one container cold to provide good quality meals to senior elders. Hot meals should be kept at least 60 degrees Celsius or more, and chilled meals should be kept at least 4.4 degrees Celsius to keep the meals safe.

We will provide more information in our second letter.

Thank you for your assistance.
Neva Elijah
EatEZ Community Outreach Director
NElijah@EatEZ.com

(a)

EatEZ

To: Engineering Students
From: EatEZ Organization
Subject: Request for Design Idea

Dear Engineering Student Designers,

Thanks for agreeing to work on this project. We highly appreciate your time and effort.

In the first letter, we have shared our meal delivery problem with you. As we said before, we need individualized insulated bags that are easy to use and can maintain the temperature of food for a couple of hours, which are made for senior citizens.

In this letter, we aim to provide you with more information about what we need.

Our organization agreed on a standard-size food container that would go inside the individualized bag/box that you were initially asked to design. The dimension of the food container is 6.5"W x 9.25"L x 2.75"H. The container is usually made of light plastic. The food container weighs less than 1.5lbs. The single container should be able to contain both hot and cold items. The bag/box that you design should eliminate the risk of food spilling. Finally, the bags/boxes should be easy to carry and open.

We look forward to seeing your solutions.

Thank you for your assistance.

Neva Elijah
EatEZ Community Director of Outreach

(b)

Fig. 1. The EatEZ client memo (a) part 1 presented week three, and (b) part II presented week five.

whale blubber, etc.). Students engaged in tough decision-making about what designs they thought would be best, applying their understanding of nature and thermoregulation as they designed potential solutions [12, 13, 24]. Table 3 highlights the weekly themes of unit 1.

The unit aligned with the state's Career, Technical, and Agricultural Education (CTAE) and Engineering standards as well as the NGSS (HS-ETS 1–3). The 50-minute lessons were developed using the 5E learning cycle [65], which provided a structure for students to connect their ideas with their experiences and apply their learning to new contexts [66, 12, 24]. Each lesson began with an 'engage' component, referred to as "BID WOWs," illustrating how nature has been utilized to create products and design solutions to ground students' thinking when applying high-level concepts of BID.

2.5 Data Sources

The data sources included classroom observation field notes, final presentations, and semi-structured focus group interviews conducted at the end of the unit implementation. Each data source is described below.

Classroom observations of students and the teacher were conducted across the seven weeks of the unit implementation. The students were observed to determine how they interacted with their peers within and outside of their assigned teams, as well as how they interacted with their teacher during the unit activities and their overall engagement in the EDP throughout the unit [12, 24]. Meanwhile, teacher observations entailed implementation of the curriculum, pedagogy, and the teacher's role during implementation. Detailed field notes, including images of designs, were documented during the observations.

Student groups presented their lunchbox design solutions as their final class presentation for their classmates and teacher. The presentations were seven minutes in length and required students to identify the problem, describe the different thermal regulation systems in nature (i.e., polar bear, whale blubber, camel's hump, etc.) they explored for their design solution, which system(s) where incorporated into their design and how they were incorporated. For instance, a polar bear's blubber and fur help to insulate the polar bear by preventing heat loss from the body, so including multiple layers of insulation prevents the food from getting cold and maintains the required temperature. Further, students presented their design iterations along with results and modifications for each design, leading to their final design solution. The presentations were audio-recorded and transcribed for data analysis.

Table 3. BIRDEE unit 1 weekly theme and description

Weeks	Themes and Description of each week
Week 1	**Launcher: Connecting Nature to the Engineering Design Process** • Students explore nature and select an object to describe by conducting a structure, function, and mechanism analysis. Students are introduced to BID and how it relates to the engineering design process. They are presented with the dirty shoe problem and brainstorm to understand the problem, user needs, and design requirements. The week ends with students developing a problem statement leading to ideating their first conceptual design.
Week 2	**Launcher: The Lotus Effect** • Students explored systems, learned about the lotus leaf, and engaged in benchtop prototyping to test Neverwet (Lotus Effect), a water-repellent solution, on multiple surfaces and fabric. Afterward, the team created the second conceptual design. The final designs were shared and evaluated by another team, finalized, and then presented to the whole class.
Week 3	**Design Challenge: Identify and understand** • Students are presented with a client memo from EatEZ asking them to create a better delivery system. Students identify the problem, which encompasses using the 4-box tool for problem specification. They understand the design requirements, conduct market research, and identify customer needs.
Week 4	**Design Challenge: Heat Transfer and Thermoregulation** • Students explore to understand thermal regulation systems in nature, conduct structure, function, mechanism (SFM) analysis, and design their first conceptual design. Afterwards they conduct a thermal regulation experiment, using a jar covered with their choice of insulator (i.e., cotton, bubble wrap, aluminum) filled with ice and a temperature sensor to record data. They analyze the results to determine the best insulator.
Week 5	**Design Challenge: Ideation and Evaluation** • Students are presented with the second memo from EatEZ that includes more details pertaining to their design. Students make changes to their problem statement and conceptualize the second design, which includes design requirements from the first and second memos as well as what they have learned from their thermal regulation experiment. Additionally, students are introduced to the morpho matrix tools and use these tools to design their third conceptual design.
Week 6	**Design Challenge: Prototype and Test** • Students prototype each conceptual design and evaluate their design using the temperature sensors. This is an iterative process that extended to week seven if needed.
Week 7	**Design Challenge: Communicate Solution** • Students finalize their prototypes, presentation and get ready to share with their classmates.

Additionally, we conducted semi-structured focus groups with student teams at the end of the unit implementation. The interviews took approximately 45 minutes. In the interviews, we asked students '*how*' and '*what*' questions regarding their utilization of the EDP, perceptions about the unit, BID integration in engineering, and experience working in teams [64]. The focus group interviews were audio-recorded and transcribed for data analysis.

2.6 Data Analysis

We utilized qualitative thematic analysis to explore how students employed biological systems taught in the BID-focused curriculum to design solutions [67]. Qualitative thematic analysis is the process of identifying patterns or themes within qualitative data, which may include transcribed communications, such as semi-structured interviews, images, and written text to describe the meaning of the material [68]. Thematic analysis is a useful method for examining the perspectives of different research participants, highlighting similarities and differences, and generating unanticipated insights [67]; [69]. Further, it is an effective method for summarizing key features of a large data set because it forces the researcher to utilize a well-structured approach to handling data, helping to produce a clear and organized final report [70]. The thematic analysis enabled us to explore students' integration of BID within the engineering design process holistically and systematically.

Braun and Clark's [67] six-step method was utilized for thematic analysis, which consists of *(1) becoming familiar with the data, (2) generating codes, (3) generating themes, (4) reviewing themes, (5) defining and naming themes, and (6) locating exemplars*. Members of the research team first engaged in cycles of reading the data, with each cycle generating further insights and multiple codes and applying them to contextual segments. This was followed by generating over-arching themes. The generated codes were sorted into these high-level themes and 'exemplars' for each theme identified. The whole process was iterative, and throughout, researchers engaged in deep discussions, constantly comparing and sorting the data until a robust set of themes was finalized. Table 4 provides a list of the final agreed-upon overarching themes, along with a description of each theme generated through analysis and deep discussions.

In order to establish trustworthiness, coding was performed by two researchers on the team, with an additional third researcher on the team providing checks throughout the coding process. All the coders who assisted with coding have expertise in

Table 4. Themes and definition

Theme	Definitions
Criteria/constraint	Students identified the criteria and constraints to understand client and user needs.
Integration of Biologically inspired design (BID) in engineering design process (EDP)	Students acknowledge inspiration from a biological organism and research to learn about potentially applicable biological functions.
Decisions-making (prototyping, evaluations, and BID decisions)	Students engage in decision-making processes to better their lunchbox design.
Internalizing of structure, function, and mechanism	Students demonstrate awareness of structure, function, and mechanism (SFM) analysis to better design their BID-inspired lunchboxes.

secondary science and engineering. At some level, they contributed to the development of the unit and thus were familiar with the content covered in the unit, including BID integration. All data was coded to an exact agreement, which also encompassed agreement on the definition of each theme.

The manuscript's results are organized around themes that emerged from the data, highlighted in Table 4. For participant anonymity and clarity, the following identifiers are used: focus group team # (FGT#), final presentation team # (FPT#), and Field Notes (FN).

3. Findings and Discussion

The findings revealed four major themes: Criteria/ Constraints, Integration of Biologically inspired design (BID) in the engineering design process (EDP), Decision-making (prototyping, evaluations, and BID decisions), and Internalizing Structure, Function, and Mechanism.

3.1 Students Identify the Criteria /Constraints

The theme *criteria/constraints* describes students realizing that identifying criteria and constraints is a critical aspect of the EDP. In fact, students engaging in the unit were compelled to reference the design criteria and constraints when ideating possible design solutions through various activities and experiments related to the challenge. Hence, during their focus groups, many groups claimed that they began by identifying the user, user needs, and design requirements when probed about how they employed the EDP to solve their design problem. For instance, Team Two claimed,

> "We first started by seeing what the requirements were for the user. So, we were learning about what they [EZeats] want and why they want it and trying to understand the problem. Based on that, we then made a problem statement. And then, after we made the problem statement, we started seeing ways that we could try to solve the problem" (sic, FGT#2).

Another team claimed writing the problem statement was the first step as it helped to identify the need and who the need was for, "first, we wrote a problem statement, identifying what our user needs and what difficulties they face. And then put what are the requirements that we need to have for our box to be successful" (sic, FGT#13). Similarly, during their presentation, Team One started with, "So, we have some requirements here: it has to be easy to hold. And it should keep the food hot or cold, like, depends on the food, it should keep the ice cream colder and hot foods hotter" (FPT#1).

In addition, one team claimed that while understanding the problem was critical for identifying the criteria/constraints, testing the prototype was equally important to verify if the requirements were met.

> "I think understanding the problem is really important, but also testing the prototype that we made because it helped us make sure that the requirements were met because we would not know without testing. Obviously, I understand the problem because we need to know what they want before we just create something that they would not like" (FGT#2).

Likewise, Team Fifteen claimed, "I would say probably understanding the requirements and the prototype. Because based on your understanding of the requirements, you are building the prototypes in which then both of those build off your final product" (sic, FG#15).

Many students also coupled the 'identifying the problem' with the 'understand' stage of the EDP since they recognized that without knowing the design requirement, it would be difficult to conceptualize and ideate an initial design. Another asserted that they need to "understand" (FGT#6) first what is being asked to proceed, as it is difficult to ideate a possible solution without knowing the problem and requirements. This theme of identifying the criteria/constraints carried on across the data, including in students' final presentations. All teams in their final presentation commenced their presentation by identifying the user and their needs, followed by the design requirements. For example,

> "The requirements are that the hot food should stay at 60 degrees Celsius. The cold food should stay at 4.4 degrees Celsius. It should be easy to distinguish. It should stay the same temperature for one to two hours. It should be easy to carry, and there should be no spills, and it should fit two lunchboxes. The old design was a

> cooler, but now we are trying to improve it to make it better" (sic, FPT#4).

In each of these examples, it was evident that students recognized that understanding the user, their problem, and their requirement was an essential aspect of the design process. They all realized that it was the first step to conceptualizing a possible BID-integrated design solution. Therefore, reading and re-reading the client memo to pinpoint the essential components was observed during lesson implementation, as noted in the field notes (FN). Further, students indicated that identifying the criteria/constraints provided them with a means to articulate the knowledge they acquired about the problem and aided with evaluating their BID-integrated design solutions. Interestingly, while all student teams highlighted design criteria/constraints, they failed to discuss any market research that may have been conducted or were planning to conduct to explore existing solutions that have been inspired by nature.

This theme provided evidence that while students felt that identifying the problem is a critical aspect of EDP, it is also one that is challenging and requires a deep dive into the problem statement. Especially for this design problem, students felt it was even more relevant for them to understand the design criteria/constraints and user needs because they needed to find the best possible BID-inspired solution that could meet the desired requirements (i.e., temperature/size). Nonetheless, students indicated that this helped them understand the BID-integrated engineering design challenge and design requirements better. Moreover, it compelled them to explore and understand natural systems that regulate the temperature most suitable for their design solution.

Research shows that engaging in problem scoping, as well as recognizing the importance of problem scoping in engineering design, can be challenging for beginning designers. Beginning designers start designing the solution before they understand the challenge and skip conducting research or gathering limited information, which may result in a superficial solution [71]. Since engineering design problems are often ill-defined and complex, simply understanding the problem does not equate to being an informed designer [71]. Rather, identifying the problem, including criteria and constraints, is an iterative process where designers actively engage in this phase throughout the EDP [71]. Therefore, for beginning designers to understand the space of the problem and solution, time at the beginning and throughout the design process needs to be spent and allotted to define the problem, understand the requirements, and conduct research [71–73].

3.2 Integration of Biologically Inspired Design in Engineering Design Process

The theme *Integration of BID in the EDP* is defined as students acknowledging inspiration from biological organisms and research to learn about potentially applicable biological functions and conducting SFM analysis to break down biological systems to understand how and if that system is applicable to the design solution. Many student teams identified the biological organism that inspired their design solution, even elaborating further to explain what functional aspect they incorporated into their design solution. For instance, one team stated that they were inspired by polar bear and their ability to insulate,

> "We thought of a polar bear, and we thought about how they were insulating themselves, and we learned about it through the activity that we were talking about around the room [gallery walk]. So, I think based on that, we were able to get some ideas of what we wanted to do and then use the same system [for our] problem" (FGT#2).

The team in this quote highlights the gallery walk, an activity in which they conducted a biological search by exploring organisms (i.e., polar bear, whale blubber, camel's hump, etc.) in nature that thermoregulate and then identified structures that perform similar functions. Likewise, another team claimed, "We used the idea of the penguin's wing for the biologically inspired design. The penguins have multiple layers of insulation, and that is what we used for the lunchbox" (FGT#18). Another team asserted, "We used an idea from the polar bear and its blubber and how that concentrates it and keeps the heat inside. We also applied that for the cold [portion of the lunchbox] to keep the cold inside. I think it is like an insulator" (FGT#7).

Students were inspired by multiple organisms, many of which they explored during the activities, and others they searched on their own to learn about potential applicable biological functions. For example, one team searched and discovered a variety of biological organisms that could be an inspiration for their design solution,

> "We researched what animals keep themselves insulated the most. We found penguins and polar bears since they live in cold environments. Then, for thermal regulation, I think we found dogs and iguanas. Since they live in hot environments, they pant to make themselves cold, and they cannot really sweat. So, they were using different ways" (sic, FGT#3).

Another team initially searched for other biological systems in nature but then opted to use what they had learned about within the unit lesson and through engagement in activities. Team Eleven explained the biological system they chose in their final design solution and the reason they selected that organism.

> "I would say the things around us, like nature and our lunchboxes, [were] our inspiration. And then, animals. We used whales as our biological inspire design because they have [many] layers that help them insulate the temperature and stay warm when they are in deep, cold waters. So that is why in our lunchbox, we added aluminum foil, mesh, felt, and bubble wrap just to regulate the temperature inside and fit the elders' requirements" (FGT#11).

Similarly, Team Eight was also inspired by the structures and functions of an organism and used materials that would mimic those features, such as insulation, to meet the design temperature requirements. Team Eight asserted,

> "Our inspiration was the blubber, the layer of blubber that polar bears have. The blubber helps to keep the heat within the polar bear and to ensure that it does not escape, similar to Styrofoam. Styrofoam also helps to ensure that heat does not escape from things, so we took the biologically inspired design and put Styrofoam into our box" (FGT#8).

Throughout the unit, students were exposed to many biological organisms that displayed thermoregulation behaviors. Thus, many teams were quick to recognize and identify biological organisms that inspired their design solution. Nonetheless, it was challenging for some teams even though many examples were presented in the unit activities. Team Six stated, "It was hard to come up with which animals would fit the solution best, but as I said, it was fun to find solutions in nature" (FGT#6). Analogously, another team pointed out, "I feel like yes, because sometimes there was not anything that we could find specifically in biology, so we really had to dig. I think it was kind of hard to draw inspiration from biology" (FGT #9). Some teams felt that while there were multiple options available, each organism was unique in regard to its structural and functional components. Therefore, deciphering which should be considered for their design solution was difficult to determine. For instance, Team Twelve claimed, "We have to find which animal we can use to use for inspiration. . . . Because there are many animals and some of them have different structures and components and stuff like that" (FGT#12). This was also evident during class observations; often, student groups were heard discussing various animals and their key features (i.e., polar bear, penguin, jackrabbit, and arctic hare) and which one would be best to mimic thermoregulation (FN). Consequently, groups would then refer back to the data they had gathered about materials (i.e., cloth, aluminum, bubble wrap) and their ability to regulate temperatures (FN), trying to connect each material with the biological system to use for their lunchbox design.

This theme provided evidence that teams integrated BID in the EDP overall by exploring, understanding, and analyzing biological systems using SFM breakdown and biological analogies, even though the integration of SFM was limited to the structure and function level. Further, the exposure to various BID activities, such as the gallery walk, encouraged students to reflect on natural systems for their design solutions. Wissa et al. [74] note that recent advancements in computation and fabrication enable opportunities for engineering innovation via BID. However, mapping or extracting biological connections and elements to engineering design is challenging for students due to the complexity of biological organisms [75]. In essence, students tend to focus on structure rather than function when analyzing a biological system [75]. Nonetheless, BID within the EDP can offer students the opportunity to view nature differently. This new-found appreciation for and knowledge about nature could result, as highlighted in previous literature that has documented the relationship between increased knowledge and environmental attitudes [76–78].

3.3 Students Engaged in Decision-Making (Prototyping, Evaluations, and BID Decisions)

The theme of *decision-making* signifies students' engagement in decision-making processes to improve their lunchbox design. Student teams were observed reflecting on, discussing, and evaluating their design decisions and solutions (FN) at various stages in the EDP (ideate, prototype, and evaluate). Students engaged in rich discussions with their team members to decide if the prototype met the desired requirement. Furthermore, when asked during the focus group interview what led them to make modifications to their designs, students were quick to explain that any alterations were made after they evaluated their prototypes against the desired requirements. For instance, Team Fifteen asserted,

> "[In our] first box, we did not have to really do anything to it, but we decided to add insulation to it. We had just one layer of insulation and then some plastic wrap around that as well. And nothing really for the cold, but we built that for the second one, where we realized that would not really do much, so we had to add more. We added more layers of Styrofoam and bubble wrap, as well as aluminum foil and insulation [for the] second prototype. And then when we thought of it, we were like, "We need a handle." We added some plastic just to make it another level and add some more. We were continuously thinking about our requirements, making sure that we met all of them" (sic, FGT#15).

Team Seven modified their lunchbox design to make it "visually appealing" by wrapping the lunchbox with colored tape. Further, the team added additional insulation to the design solution after prototyping and testing. Team Seven notes,

> "[We] also made the wood thicker because [it] felt like it would do better at separating the heat from each other since wood does not conduct heat (sic). We also changed the insulation. Initially, we found just a combination of random household materials. Here, we actually had insulation, and I think it is called conductive tape" (FGT#7).

For some, the evaluation stage of the EDP engaged them in decision-making that aided in identifying the components in the design that worked, were necessary, and/or were impractical. Team Seventeen highlighted that during the evaluation, we reflected on "why it would work and why it would not work?" (FGT#17). Consequently, they removed the cup holder from their lunchbox from their original prototype. In contrast, Team Six discussed the practicality of the design and how it triggered them to engage in a discussion of whether modifications were necessary. The team ultimately decided to revise their original prototype. As the team claimed,

> "So, practicality is something that we also considered when we were doing this based on what he said about the zippers. We originally had two that we were planning on doing, but it was more practical just to have one, and then we changed it to the latch that we used, which was easier than what we previously had." (FGT#6).

Likewise, Team Nine also felt some features of their design were not feasible and functional. After evaluating their original prototype to determine if it met the desired requirements, the team decided to amend their prototype. As the team claimed, "Some things were not fit. We had a hot pocket design or something. We had a bunch of compartments, but we put hand warmers or something in them, but that was too impractical, so we did not do that" (FGT#9).

This theme highlighted that the iterative nature of EDP encouraged teams to evaluate and modify their original prototypes. It was evident across the data set that decision-making was prevalent during the evaluation, prototype, and test stages of the EDP. Decision-making was an important aspect of design improvement and BID integration, as it allowed them to be reflective at various levels (i.e., feasibility of design, appropriate biological system) and stages (i.e., ideate, prototype, evaluate) of the EDP. Further, design modification allowed students to be conscientious about their decisions as many, when discussing the changes, were able to justify why those modifications were necessary. Consistent with the literature, the EDP is useful for students to internalize that "engineering is about organizing thoughts to improve decision-making for the purpose of developing high-quality solutions and/or products to problems" [79, p. 10]. Decision-making is essential across all engineering disciplines and a skill highlighted in A Framework of K-12 Science Education (NRC [80]). Hence, the inclusion of engineering and EDP in pre-college education can prepare students to become better decision-makers, collaborators, and problem-solvers [81].

3.4 Internalizing of Structure, Function, and Mechanism

The last theme, *Internalizing Structure, Function, and Mechanism* (SFM), demonstrates students' awareness of SFM analysis as a means to design their BID-inspired lunchboxes. This theme was evident when teams emphasized the characteristics of their lunchbox design and how they incorporated biological systems in their lunchbox design. Moreover, practicing SFM from the unit theme was also apparent when teams elaborated on how they analyzed biological systems, referencing some of the unit activities that students engaged in to learn about BID integration in engineering.

The BID integration in EDP required students to apply biological strategies, such as SFM, to analyze biological systems. Further, students engaged in SFM analysis throughout the unit, which included analysis of biological (i.e., polar bear, camel, hare) and manufactured systems (i.e., nails, screws) leading to their design solution. The examples below illustrate how students displayed awareness of SFM for their lunchbox designs.

> "Okay. So, we had three main designs. They had different structures. One of them was a backpack. One of them, I am pretty sure, had a shoulder strap, and one of them, you held it like a briefcase. So, we picked one of them, and then... we built off of that first one that we picked. I think it was the one where we were carrying it just by the handles, like a briefcase. And then eventually, we modified the structure of it and the dimensions." (FGT#8).
>
> "Our biologically inspired design was a polar bear and an Arctic Hare. So, the polar bear... Polar bears thrive in the cold, and this is because of their warm coat. So, our insulation was inspired by their warm coats. The Arctic Hare has short, thin ears, and even though they have short, thin ears, their ears are one of their best elements" (sic, FGT#1).

During their final presentation, the same team went on to explain how BID was incorporated into their final prototype, displaying awareness of the SFM of a polar bear.

> "Furthermore, they are mostly made of fat, and fat makes up 20% of their body, and our insulation panels

inside the box are made of fat. This is the front angle of our prototype, and we use sticky notes to label each part, so that is the top part. And we put in a handle, and I think the handle worked nicely because it was easy to carry around. Then, this is the inside angle. We used aluminum foil at first, and then we used wires to split hot and cold food items." (FPT#1).

Likewise, Teams Two, Three, and Four explained during their presentation how they integrated BID in their final design, connecting it to SFM, which a polar bear and penguin inspired.

"We made it based on a polar bear because, in a polar bear, multiple layers help with heat absorption. So, this is how we included multiple layers, such as bubble wrap and aluminum foil, and there was also a divider." (FPT#2).

"And when you open it [the cover of the box], there is a side for hot food and cold food, and this is our strap. This product was inspired by the penguin because the feathers and the insulated skin were both able to trap heat in the cold" (sic, FPT#3).

"The prototype uses felt, cardboard, and polyurethane foam. Felt is biologically inspired by penguin feathers. Penguin feathers protect penguins from the cold Arctic by stopping heat from entering or leaving, just like the felt acts" (FPT#4).

These examples for the theme of *Internalizing SFM* illustrate how student teams incorporated biological systems in their lunch box design, specifically what functional and structural features of the biological system were used in their final design to create the insulating function.

Students' understanding of SFM was also evident in their explanation of how they analyzed systems presented in the unit activities, such as the 'gallery walk' or the 'found object.' As stated earlier, several activities were embedded in the unit, which was intended to expose and scaffold students' understanding of SFM breakdown. One specific activity in the unit was the 'Found Object' activity. In this activity, students were required to explore nature and find a natural object that is intriguing or unusual. Afterward, they analyzed the object they found in terms of its physical structure, basic function, and mechanism. This activity was intended to expose students to nature, SFM, and how nature can be an inspiration for designing solutions. The examples below highlight the objects student teams selected and their understanding of SFM.

"Well, during the activity, we went to find something that was really some item, and we bought it inside, and we tried to look at the components and functions of the item. I took a pinecone, and I saw that when you break it apart, there is an inner core, and then there are the little stem things. I do not know what they are called, but they are stem things, and they have a specific pattern on the pinecone. I was able to explain *how they opened up, and that helped. So that is what we did for that activity.*" (FG#T2).

"Yeah, I remember I bought a piece of grass. I remember looking at it through a magnifying glass, I guess. I saw different aspects of how many pieces of grass we have. And I remember trying to figure out which function we have helped the grass to grow" (FGT#11).

"We talked about how. . . I think it was a roly-poly. It was about, we looked at a roly-poly. We were talking about how the number of legs that they had made the bug move faster, or the protective shell around the roly-poly, they would curl up in a ball when they were being invaded or something, for protection. So, I do not think that was for the lunchbox, but it made me think of more structure and, mechanism-wise, at least" (FGT#1).

"So, for me, I did bees, and I did penguin feathers. So, for bees, you had to read about how they can control their muscles and hustle together to create heat. How penguin's feathers and, I guess, I want to say blubber. They have more fat but protect them from the cold water and the cold breeze. Basically, to break it down, you just wrote what the functions *did, the different parts, and some drawings*" (sic, FGT#4).

Within this theme, three concepts were evident based on students' responses and explanations. First, some students highlighted how they incorporated SFM in their design solution, suggesting that students engaged in BID during the understand and ideation stages of EDP to enable them to identify biological functions, mechanisms and structures that were a source of inspiration. Secondly, the SFM breakdown employed for multiple activities throughout the unit and challenge changed how they viewed and employed nature for their engineered solution. Thirdly, when conducting SFM analysis, some students gave importance to the structure of the organism rather than the function, demonstrating that novice designers concentrate on structure compared to informed designers who tend to focus on function. While many students were able to demonstrate knowledge of structure and function to some degree, as evident in the findings, their understanding of and ability to fully explain function and mechanisms was absent. This finding was also supported by the literature that students have difficulty learning about complex systems [81]. While students can identify relevant structural components, accurately describing causal behaviors or mechanisms of systems is more challenging [82]. This may be an issue related to the ambiguity in the meaning of the phrase structure, function, mechanism as a whole, as well as the individual contributing terms, especially among students [82, 83]. Therefore, such knowledge must be implemented more broadly within the K-12 setting, as it can expose students to different approaches to system conceptualization [82]. Moreover, the use of SFM analysis to break down biological systems grants individuals the ability to view nature around them differently [76]. This new viewpoint transitions the viewer from looking at nature passively for enjoyment to viewing biological entities as an abundant resource for engineering inspiration [76].

4. Discussion

This research is centered within a K-12 setting, focusing on students' use of BID within the EDP to solve the design challenge as a result of their participation in the design-based BID engineering curriculum. The findings of this study build on concurrent research that explored the students' experiences utilizing BID [13], teachers' implementation of the BID-integrated curriculum [12], and activities within the BID-focused curriculum that fostered students' engagement in learning [24]. Further, this study extends the existing literature on BID-integrated learning experiences for students in K-12 education [17, 18, 22, 23, 26, 84].

This study highlights the importance of BID integration in pre-college engineering classrooms. Several findings are evident. First, during the curriculum implementation, students engaged in EDP holistically and iteratively to solve the given design challenge. Throughout their use and engagement in EDP, they reflected on the criteria/constraints and continuously evaluated the intended outcomes against their prototypes. The nature and layout of the curriculum forced the students to spend certain amounts of time on each of the activities and phases of design; nonetheless, several students still recognized the importance of allocating time for problem identification and understanding.

Secondly, students integrated BID into the EDP to solve their design problem. Across the teams, students acknowledged that a biological organism inspired their design solutions, and they conducted research to learn about potentially applicable biological functions. Consequently, through this deep dive into the biological systems, students learned about and engaged in SFM analysis. However, the BID integration was limited to structure and function. However, as a result of this integration, students recognized the potential for biology to act as a source of inspiration for ideas, which was apparent in their final prototype solutions.

Thirdly, DBL supported students' understanding of BID in engineering as a result of their engagement in the BID-focused engineering unit. The BID integrated design challenge promoted students' engagement in the iterative EDP to develop an innovative solution by applying knowledge of biological systems and engineering core ideas [50]. As students iteratively conceptualized and created a solution, they were compelled to engage in complex and interwoven inquiry and design processes [24]. Further, the DBL environment fostered collaboration and active engagement in the learning process, allowing students to participate in deep discussions, idea generation, and evaluation with their team members [53].

Lastly, the EDP was an effective process to promote BID in high school engineering. EDP enabled the integration of scientific lessons (biology/BID). At the same time, the interactive BID activities supported students' use of both engineering and biological principles to solve an engineering design problem. This integration also promoted critical skills such as problem-solving and decision-making. The EDP, coupled with BID integration, facilitated students' iterative engagement in problem formulation, ideation, and evaluation to develop effective and sustainable design solutions. Furthermore, the EDP fostered the use of analogical design tools that facilitated a transfer of biological strategies to the design challenge [11, 12, 14], encouraging students to think about how nature can be applied to solve modern-day engineering problems. Meanwhile, the engineering design challenge supported learning across multiple disciplines through engagement in the EDP.

5. Implication

This study has implications for the broad integration of BID in pre-college engineering classrooms. While there is extensive integration of engineering and EDP into STEM activities, the integration of BID in engineering is still scarce since it is difficult to apply biological concepts appropriately in EDP [83]. Further, the integration of BID may also be challenging due to engineering teachers' lack of biological knowledge [11, 12]. Hence, more opportunities are needed for students in K-12 to be exposed to BID in engineering through curriculum development. To effectively integrate EDP in biology learning, appropriate support for engineering design in high schools, including teacher professional development, is equally necessary [11, 39, 85].

6. Limitation

First, this study was conducted at a single school, and the data was collected from a purposively selected group of students, as described in the methods. Results are not intended to be generalizable but rather to demonstrate the experiences of engineering high school students and their application of BID integration in engineering.

Second, the number of participants was small, as participation in the research was voluntary. Student participants were instructor-selected and assigned to teams; consequently, they may or may not represent the full spectrum of experiences and learning, which may have contributed to bias in the results.

7. Conclusion

In conclusion, the results of this study emphasize the critical role of identifying criteria and constraints during the utilization of the EDP, particularly in the context of design challenges. The findings reveal that students recognized the importance of understanding the problem statement and design requirements as the foundational step toward conceptualizing and ideating effective design solutions. Through various activities and engagements, students consistently referenced design criteria and constraints, emphasizing the significance of this initial phase in the EDP.

Furthermore, the integration of BID into the EDP demonstrated students' willingness to explore and analyze natural systems for engineering solutions. Students drew inspiration from diverse biological concepts, utilizing SFM analysis to inform their design decisions. Despite some of the challenges, students displayed a newfound appreciation for nature's ingenuity and its potential applications in engineering.

Lastly, the theme of Decision-Making highlighted students' active engagement in iterative design processes, where design requirements and practical considerations informed the evaluation and modification of prototypes. This iterative approach not only improved the quality of their design solutions but also fostered critical thinking and reflection, essential skills for future engineers.

Overall, this study highlights the importance of scaffolded learning experiences that emphasize problem scoping, BID integration, decision-making, and SFM analysis in the pre-college engineering curriculum. By nurturing these skills, educators can empower students to become proficient problem-solvers, collaborators, and innovators equipped to tackle complex real-world challenges in engineering and beyond.

Acknowledgment –We would like to acknowledge National Science Foundation Grant No. 1907906 for supporting this work. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

We would like to thank graduate assistants Alexandra Towner and Atiya Jangda for their contributions to data organization and assistance in the analysis of this work. We would also like to acknowledge and thank our entire BIRDEE team including Jeffery Rosen and Julia Varnedoe for their work on the development of the BIRDEE curriculum,. Finally, thank you to all of the amazing teachers who opened their classrooms to us for the BIRDEE project.

References

1. J. K. S. Nagel and R. M. Pidaparti, Significance, prevalence and implications for bioinspired design courses in the undergraduate engineering curriculum*, International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, **50138**, p. V003T04A009, 2016.
2. R. B. Stone., A. K., Goel and D. A. McAdams, Charting a course for computer-aided bio-inspired design, *Biologically Inspired Design: Computational Methods and Tools*, pp. 1–16, 2014.
3. M. Weissburg, C. Tovey and J. Yen, Enhancing innovation through biologically inspired design, *Advances in Natural Science*, **3**(2), pp. 01–16. 2010.
4. P. E. Fayemi, K. Wanieck, C. Zollfrank, N. Maranzana and A. Aoussat, Biomimetics: process, tools and 8 © 2022 by ASME practice, *Bioinspiration & Biomimetics*, **12**(1), p. 011002, 2017.
5. J. M. Benyus, *Biomimicry: Innovation inspired by nature*. Morrow New York, 1997.
6. S. Vogel, *Cats' paws and catapults: Mechanical worlds of nature and people*. WW Norton & Company, 2000.
7. K. Goel, B. Bras, M. Helms, S. Rugaber, C Tovey, S. Vattam, M. Weissburg, B. Wiltgen and J. Yen, Design patterns and cross-domain analogies in biologically inspired sustainable design," in *2011 AAAI Spring Symposium Series*, 2011.
8. D. Vandevenne, T. Pieters and J. R. Duflou, Enhancing novelty with knowledge-based support for biologically inspired design, *Design Studies*, **46**, pp. 152–173, 2016.
9. D. G. Jansson and S. M. Smith, Design fixation, *Design Studies*, **12**(1), pp. 3–11, 1991.
10. D. P. Moreno, L. T. Blessing, M. C. Yang, A. A. Hernández and K. L. Wood, Overcoming design fixation: Design by analogy studies and nonintuitive findings, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, **30**(2), pp. 185–199, 2016.
11. A. P. Rehmat, A., Towner, M. Alemdar, R. Moore, M. Helms, J. Rosen, J. Varnedoe and M. Weissburg, Biologically inspired design for engineering education: A multiple year evaluation of teachers' professional learning experiences (Evaluation). *In ASEE Annual Conference & Exposition*, 2022.
12. A. P. Rehmat, A. A. Towner, M. Alemdar, M. Helms, D. B. Porter, R. Moore and J. Rosen, and M. Weissburg, A case study investigating high school teachers' implementation of an engineering-focused biologically inspired design curriculum (Fundamental Research). *In ASEE Annual Conference & Exposition, 2023.*
13. M. Alemdar, D. Baptiste-Porter, A. P. Rehmat, M. E. Helms, A. Towner, R. Moore, J. Rosen and M. Weissburg, Biologically inspired design for high school students (Work in Progress), *Proceedings for the 130th Annual Conference and Exposition of American Society for Engineering Education (ASEE).* Baltimore: Maryland, 2023.
14. R. A. Moore, H. Ehsan, K. Euisum, M. Helms, M. Alemdar, J. Rosen, C. Cappelli and M. Weissburg, Creating Biologically Inspired Design Units for High School Engineering Courses, *Institute of Electrical and Electronics Engineers Frontiers in Engineering Education*, 2022.

15. Lead States, NGSS, *Next generation science standards: For states, by state*s, The National Academies Press Washington, DC., 2013.
16. D. Rhoten and S. Pfirman, Women in interdisciplinary science: Exploring preferences and *consequences, Res. Policy*, **36**(1), pp. 56–75, 2007.
17. C. Sabo, M. Mullen, and A. Burrows, Teaching Bio-Inspired Engineering in K-12 Schools, *Infotech@ Aerospace*, p. 1601, 2011.
18. D. Bernstein, G. Puttick, K. Wendell, F. Shaw, E. Danahy and M. Cassidy, Designing biomimetic robots: iterative development of an integrated technology design curriculum, *Educational Technology Research, and Development*, pp. 1–29, 2022.
19. T. D. Snyder, C. De Brey and S. A. Dillow, Digest of Education Statistics 2016, NCES 2017-094, *National Center for Education Statistics*, 2018.
20. S. L. Eddy, S. E. Brownell and M. P. Wenderoth, Gender gaps in achievement and participation in multiple introductory biology classrooms, *CBE – Life Sciences Education*, **13**(3), pp. 478–492, 2014.
21. G. D. Kuh, Excerpt from high-impact educational practices: What they are, who has access to them, and why they matter, *Association of American Colleges and Universities*, **14**(3), pp. 28–29, 2008.
22. F. Tauro, Y. Cha, F. Rahim, M. S. Rasul, K. Osman, L. Halim, D. Dennisur, B. Esner and M. Porfiri, Integrating mechatronics in project-based learning of Malaysian high school students and teachers, *Int. J. Mech. Eng. Educ*., (**45**)4, pp. 297–320, 2017.
23. J. Laut, T. Bartolini and M. Porfiri, Bioinspiring an interest in STEM, *IEEE Transactions on Education*, **58**(1), pp. 48–55, 2014.
24. A. P. Rehmat, M. Alemdar, M. Helms, D. Baptiste-Porter, J. Rosen and M. Weissburg, M. Biologically inspired design: high school Students' engagement in BID integrated learning in engineering classrooms. *In 2023 IEEE Frontiers in Education Conference* (FIE), pp. 1–7. 2023.
25. C. L. Dym and L. Little, *Engineering design: A project-based introdu*ction, 2nd ed., New York, N.Y.: John Wiley, 2003.
26. R. Bailey and Z. Szabo, Assessing engineering design process knowledge, *International Journal of Engineering Education*, **22**(3), p. 508, 2007.
27. M. Mehalik and S. Christian, What constitutes good design? A review of empirical studies of design processes. *International Journal of Engineering Education*, **22**(3), p. 519. 2007.
28. H. Ehsan, J. P. Quintana-Cifuentes, S. Purzer and A. P. Rehmat, Engineering design and children: A systematic literature review, *International Journal of Education in Mathematics, Science, and Technology*, **11**(3), pp. 775–803, 2023.
29. R. Buchanan and V. Margolin, *Discovering design: explorations in design studies*. University of Chicago Press, 1995.
30. H. A. Simon, Problem forming, problem finding and problem-solving in design, *Design & Systems*, pp. 245–257, 1995.
31. D. G. Ullman, *The mechanical design process*, New York, NY: McGraw-Hill, 2003.
32. K. M. Bursic and C. J. Atman, Information gathering: A critical step for quality in the design process, *Quality Management Journal*, **4**(4), pp. 60–75, 1997.
33. J. Mangold, and S. Robinson, The engineering design process as a problem-solving and learning tool in K-12 classrooms, *In 2013 ASEE Annual Conference & Exposition*, pp. 23–1196, 2013, June.
34. K. Lin, Y. Wu, Y. Y. T., Hsu and P. J. Williams, Effects of infusing the engineering design process into STEM project-based learning to develop preservice technology teachers' engineering design thinking, *International Journal of STEM Education,* **8**, pp. 1–15, 2021.
35. M. M. Hynes, Middle-school teachers' understanding and teaching of the engineering design process: A look at subject matter and pedagogical content knowledge, *International Journal of Technology and Design Education*, **22,** pp. 345–360, 2012.
36. E. Sung, and T. R. Kelley, Identifying design process patterns: A sequential analysis study of design thinking, *International Journal of Technology and Design Education*, **29**, pp, 283–302, 2019.
37. E. Sung, and T. R. Kelley, Elementary students' engineering design process: How young students solve engineering problems, *International Journal of Science and Mathematics Education*, **21**(5), pp. 1615–1638, 2023.
38. S. C. Fan, K. C. Yu and S. J. Lou, Why do students present different design objectives in engineering design projects? *International Journal of Technology and Design Education*, **4**, pp. 1039–1060, 2018.
39. M. E. Helms, H. Ehsan, E. Kim, R. Moore, M. Alemdar, C. J. Cappelli, J. Rosen and M. Weissburg, Getting beyond the hairy house: Using structure-function-mechanism to advance biologically inspired design pedagogy, *International Design Engineering Technical Conferences and Computers and Information* by ASME *Engineering Conference*, **85420**, p. V006T06A018, 2021.
40. K. Fu, D. Moreno, M. Yang and K. L. Wood, Bio-inspired design: An overview investigating open questions from the broader field of design-by-analogy, *Journal of Mechanical Design*, **136**(11), 2014.
41. D. Gentner, Structure-mapping: A theoretical framework for analogy, *Cognitive Science*, **7**(2), 155–170, 1983.
42. K. J. Holyoak and P. Thagard, *Mental leaps: Analogy in creative thought.* The MIT Press, 1995.
43. J. S. Linsey, A. B. Markman and K. L. Wood, Design by analogy: A study of the word tree method for problem-representation, *Journal of Mechanical Design*, **134**(4), 2012.
44. D. A. McAdams and K. L. Wood, A quantitative similarity metric for design-by-analogy, *Journal of Mechanical Design*, **124**(2), pp. 173–182, 2002.
45. M. Helms, S. S. Vattam and A. K. Goel, Biologically inspired design: process and products, *Design Studies*, **30**(5), pp. 606–622, 2009.
46. M. Helms and A. Goel, The four-box method: Problem formulation and analogy evaluation in biologically inspired design, *Journal of Mechanical Design*, **136**(11), 2014.
47. J. S. Gero and U. Kannengiesser, The situated function–behavior–structure framework, *Design Studies*, **25**(4), pp. 373–391, 2004.
48. A. Goel, S. Rugaber and S. Vattam, Structure, behavior, and function of complex systems: The structure, behavior, and function modeling language, *Ai Edam*, **23**(1), pp. 23–35, 2009.
49. C. E. Hmelo-Silver, R. Jordan, C. Eberbach and S. Sinha, Systems learning with a conceptual representation: A quasi-experimental study, *Instructional Science*, **45**, pp. 53–72, 2017.
50. S. M. Gómez Puente and M. van Eijck and W. Jochems, Empirical validation of characteristics of design-based learning in higher education, *Int. J. Eng. Educ*, **29**, pp. 491–503, 2013.
51. X. Zhang, Y. Ma, Z. Jiang, S. Chandrasekaran, Y. Wang and R. Fonkoua Fofou, Application of design-based learning and outcome-based education in basic industrial engineering teaching: a new teaching method, *Sustainability*, **13**, pp. 26–32, 2021.

52. Y. Doppelt, M. M. Mehalik, C. D. Schunn, E. Silk and D. Krysinski, Engagement and achievements: A case study of design-based learning in a science context, *Journal of Technology Education*, **19**(2), pp. 22–39, 2008.
53. S. A. Azizan and N. Abu Shamsi, Design-based learning as a pedagogical approach in an online learning environment for science undergraduate students, *In Frontiers in Education*, **7**, p. 279, 2022.
54. S. Puntambekar, and J. L. Kolodner, Toward implementing distributed scaffolding: Helping students learn science from design, *Journal of Research in Science Teaching*, **42**(2), pp. 185–217, 2005.
55. L. D. English and D. T. King, STEM learning through engineering design: Fourth-grade students' investigations in aerospace, International *Journal of Stem Education*, **2**, pp. 1–18, 2015.
56. C. E. Hmelo, D. Holton and J. L. Kolodner, Designing to learn about complex systems, *Journal of Learning Sciences*, **9**, pp. 247–298, 2000.
57. C. Ford, D. McNally and K. Ford, Using design-based research in higher education innovation, *Online Learn*, **21**, pp. 50–67, 2017.
58. D. Nelson, Design-based learning delivers required standards in all subjects, Ke12, *The Cal Poly Pomona Journal of Interdisciplinary Studies*, **17**, pp. 27–36, 2004.
59. J. Strobel, J. Wang, N. R. Weber and M. Dyehouse, The role of authenticity in design-based learning environments: The case of engineering education, *Computers & Education*, **64**, pp. 143–152, 2013.
60. D. Fortus, J. Krajcik, R. C. Dershimer, R. W. Marx and R. Mamlok-Naaman, Design-based science and real-world problem-solving, *International Journal of Science Education*, **27**(7), pp. 855–879, 2005.
61. Y. Tang and X. Sun, A summary of the research on domestic design-based learning, advances in social science, education, and humanities research, *In Proceedings of the 2nd International Conference on Economics, Management Engineering, and Education Technology*, **87**, pp. 304–307, 2017.
62. L. Zhao, W. He and Y. S. Su, Innovative pedagogy and design-based research on flipped learning in higher education, *Front. Psychol*, **12**, 2021.
63. E. Fried, A. Martin, A. Esler, T. Antoine and C. Lisa, Design-based learning for a sustainable future: student outcomes resulting from a biomimicry curriculum in an evolution course, *Evol. Educ. Outreach*, **12**(22), 2020.
64. M. Sandelowski, Whatever happened to qualitative description? *Research in Nursing & Health*, **23**(4), pp. 334–340, 2000.
65. H. Banchi and R. Bell, *The many levels of inquiry, Science and Children*, **46**(2), p. 26, 2008.
66. S. Rodriguez, K. Allen, J. Harron and S. A. Qadri, Making and the 5E learning cycle, *The Science Teacher,* **86**(5), pp. 48–55, 2019.
67. V. Braun, and V. Clarke, Using thematic analysis in psychology, *Qualitative Research in Psychology*, **3**(2), pp. 77–101, 2006.
68. K. Krippendorff*, Content analysis: An introduction to its methodology.* Sage publications, 2018.
69. L. S. Nowell, J. M. Norris, D. E. White and N. J. Moules, Thematic analysis: Striving to meet the trustworthiness criteria, *International Journal of Qualitative Methods*, **16**(1), 2017.
70. N. King, Using templates in the thematic analysis of text, In *Essential Guide to Qualitative Methods in Organizational Research*, p. 256, 2004.
71. D. P. Crismond and R. S. Adams, The informed design teaching and learning matrix, *Journal of Engineering Education*, **101**(4), pp. 738–797, 2012.
72. K. Dorst and N. Cross, Creativity in the design process: Co-evolution of problem-solution, *Design Studies*, **22**(4), pp. 425–437, 2001.
73. K. A. Douglas, T. J. Moore, A. C. Johnston and H. E. Merzdorf, Informed designers? Students' reflections on their engineering design process*. International Journal of Education in Mathematics, Science and Technology*, **6**(4), pp. 443–459, 2018.
74. A. Wissa, M. Alleyne, W. C. Barley and A. V. Suarez, Best practices of bioinspired design: key themes and challenges, *Integrative and Comparative Biology*, **62**(5), pp. 1147–1152, 2022.
75. W. C. Barley, L. Ruge-Jones, A. V. Suarez, A. Wissa and M. Alleyne, Addressing diverse motivations to enable bioinspired design, *Integr Comp Biol*, 2022.
76. J. C. Bradley, T. M. Waliczek and J. M. Zajicek, Relationship between environmental knowledge and environmental attitude of high school students, *The Journal of Environmental Education*, **30**(3), pp. 17–21, 1999.
77. N. Abaid, V. Kopman and M. Porfiri, A miniature and low-cost robotic fish for ethorobotics research and engineering education: Part II – STEM Outreach, *Dynamic Systems and Control Conference*, **54754**, pp. 217–224, 2011.
78. S. Canbazoğlu Bilici, M. A. Küpeli and S. S. Guzey, Inspired by nature: an engineering design-based biomimicry activity, *Sci. Act*., **58**(2), pp. 77–88, Apr. 2021.
79. M. Hynes, M. Portsmore, E. Dare, E. Milto, C. Rogers, D. Hammer and A. Carberry, Infusing engineering design into high school STEM courses, *Publication*, 2011.
80. National Research Council, *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*, Washington, DC: The National Academies Press, 2012.
81. M. McCormick, K. B. Wendell and B. P. O'Connell, Student videos as a tool for elementary teacher development in teaching engineering: What do teachers notice?, *ASEE Annual Conference*, Indianapolis, IN. 2014.
82. C. E. Hmelo-Silver, S. Marathe and L. Liu, Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems, *The Journal of the Learning Sciences*, **16**(3), pp. 307–331, 2007.
83. R. Jain, K. Sheppard, and E. McGrath and B. Gallois, Promoting systems thinking in engineering and pre-engineering students, In *2009 Annual Conference & Exposition*, pp. 14–994, 2009.
84. K. Tipmontiane and P. J. Williams, The integration of the engineering design process in biology-related STEM activity: A review of Thai Secondary Education, *ASEAN Journal of Science and Engineering Education*, **2**(1), pp. 1–10, 2021.
85. M. Alemdar, H. Ehsan, C. Cappelli, E. Kim, R. Moore, M. Helms, J. Rosen and M. Weissburg, Biologically inspired design for engineering education: Online teacher professional learning (Evaluation), *In American Society of Engineering Education (ASEE)*, 2021.

Abeera P. Rehmat is a Research Scientist II at Georgia Institute of Technology's Center for Education Integrating Mathematics, Science, and Computing (CEISMC). Her research focuses on the development, implementation, and evaluation of integrated learning experiences in CS/engineering education across formal and informal settings for students and educators. Her research aims to cultivate critical thinking and problem-solving skills.

Meltem Alemdar is Associate Director and Principal Research Scientist at Georgia Institute of Technology's Center for Education Integrating Science, Mathematics, and Computing (CEISMC). Her research focuses on improving K-12 STEM education through research on curriculum development, teacher professional development, and student learning in integrated STEM environments.

Michael E. Helms is a Cognitive Scientist and Senior Research Scientist in the School of Mechanical Engineering and Co-Director of the Center for Biologically Inspired Design at the Georgia Institute of Technology. His research focuses on design cognition and improving design creativity, engineering education, and industry adoption of sustainable design methods. His work aims to develop a pipeline of designers and engineers proficient in developing nature-inspired, novel solutions to solve complex 21st-century problems.

Roxanne Moore is a Principal Research Engineer in the Center for Education Integrating Science, Mathematics, and Computing (CEISMC) and the G.W. Woodruff School of Mechanical Engineering at the Georgia Institute of Technology. Her research interests lie at the intersection of engineering education, design, and artificial intelligence, with a focus on cultivating inventiveness.

Marc J. Weissburg is a founding member and co-director of the Center for Biologically Inspired Design at GA Tech (founded in 2005) and has been engaged in biologically inspired design pedagogy and research for nearly two decades. He has taught BID for audiences ranging from high school students to industry professionals to career scientists and developed curriculum and best teaching practices at all of those levels. His early research helped understand how animal sensing strategies may be translated into effective methods for chemical plume tracking by autonomous vehicles. His current research examines how the organization of human infrastructure may be informed by ecological systems. Using Ecological Network Analysis, Professor Weissburg, and colleagues have examined the organization and performance of human systems at scales ranging from single industries to coupled human-natural systems, developed design rules for more resilient and sustainable human systems derived from analysis of ecological systems, and examined how these design rules can improve the efficiency of and fault tolerance of human industrial networks. Professor Weissburg is an executive member of the of the International Society of Bionic Engineering, and an editor for leading journals in the field of biomimicry, including Biomimetics.