Biological Design as an Interdisciplinary Strategy for Solving Sustainability Issues

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Abstract: This paper explores using biological design as a framework to teach problem-solving in the classroom by integrating it in design inspirations. The field of Sustainability Studies is inherently interdisciplinary and allows for the synthesis of concepts from various fields of study, humanities, social sciences, design, and STEM. Sustainability in innovation is well-recognized in the design world. Designers and engineers are focused on providing low environmental impact in their projects, and design aims are rapidly shifting from Human-centered design to Life-centered design. The concepts of biomimicry, biodesign, materials ecology, etc., are all principles that have been adapted in various technological innovations. In this paper, biological design describes the approach of combining principles of biomimicry and biodesign for finding sustainable design solutions which are the focus of a Life-centered design-based method of problem-solving. The paper presents a case study for developing learning strategies as part of a project-based interdisciplinary course, serving the honors program in the college, to teach biological design to undergraduates. Students explore theoretical concepts of biomimicry and biodesign, which they use in combination to design products to target sustainable solutions to problems addressed by the U.N. sustainable goals. The case studies developed by the student-groups demonstrate the importance of interdisciplinary thinking and further highlight the importance of integrating designs from nature for sustainability in products and architecture. Additionally, experiential learning was paramount in this course. They also developed an understanding of research, experimentation, reflection on their product, its application, economics, and, most importantly, the necessity of converting an abstract idea into a tangible 'product'. By the end of this course, students were problem-solving theoretical strategies to develop sustainable solutions using information from various disciplines. Furthermore, in this paper, we introduce the concept of 'observational digestion' as a relevant responsibility of releasing biological-designed products into the environment, thus, further enhancing the value of the principle of biological design in creating a sustainable future.

Keywords: Human-Centered, Life-Centered, Sustainability, Biomimicry, Biodesign, Biological Design.

1. Introduction

Sustainability in innovation is a well-established concept in the design world. Designers and engineers alike are focusing on low environmental impact in their projects (De Pauw et al. 2015; 2015; Vezzoli et al. 2018). The concept of sustainability as consisting of three facets, environmental, social, and economic, has become widely accepted. These areas of concern did not originate at one single point but rather evolved over time as their impact on our world and population became more apparent (Purvis et al. 2019). The connection between these three facets has encouraged a larger platform for developing strategies to keep them protected. Therefore, the focus on design strategies to address global solutions is rapidly shifting from 'Human-centered design' to 'Life-centered design' (Borthwick et al. 2022).

Human-centered design focuses on the consumer's needs as the end goal of the design (Chammas et al. 2015), which can have severe environmental consequences, in turn affecting human beings. Human-centered design is extremely popular for product development, system design, management practices and engineering frameworks. Despite its close association with human perspective, as a method of design its frequent disregard for the long-term consequences to the surrounding environments is an area for concern. This has led to more interest in engaging in life-centered design strategies (Lau 2004; Rossi and Attaianese 2023).

Life-centered design evolves human-centered design by prioritizing environmental and ethical responsibility alongside human needs (Borthwick et al. 2022). By integrating natural resource considerations and social vulnerability, this emergent framework (Ooms et al. 2022) fosters cross-disciplinary engagement and innovation (Borthwick et al. 2022). Concepts like biomimicry, biodesign, and materials ecology have been integrated into product and architectural innovations to advance this strategy.

Biomimicry, derived from "bios" (life) and "mimesis" (imitation) (Verbrugghe et al. 2023), solves design challenges using nature-inspired methods. This approach leverages nature's billions of years of evolutionary refinement, rendering the "reinvention of the wheel" unnecessary (Ilieva et al. 2022). A quintessential example is the Japanese Shinkansen bullet train. To mitigate noise pollution caused by air pressure changes in tunnels,

the chief engineer drew inspiration from the kingfisher's beak. Its drag-reducing, silent-entry mechanics allowed the train to increase speed and fuel economy (Lee and Thompson 2011). Biomimicry extends across architecture and product design (Benyus 2009). Notable examples include termite-inspired thermal regulation in Zimbabwe's Eastgate Center (Zingoni 2016), burr-inspired Velcro (Kanaani 2025), mosquito-inspired painless medical needles (Lenau et al. 2017), and whale-tubercle-inspired wind turbines (Fish et al. 2011). It also optimizes complex systems: slime mold algorithms improve urban routing (Li et al. 2020), while ant colony optimization streamlines polar shipping (Zhang et al. 2022).

Biodesign integrates living components directly into products (Myers 2012). Unlike purely "bioinspired" designs, it replaces conventional industrial systems with biological processes, ensuring inherent sustainability. It transcends biomimicry by emphasizing the interrelationship of form, function, and natural material interaction. A prime example is the Aguahoja pavilion, robotically fabricated from crustacean, apple, and tree-derived biopolymers (chitin, pectin, cellulose). The structure hardens via water evaporation and degrades upon rain exposure, returning materials to the ecosystem (Duro-Royo et al. 2017). Examples of other Biodesign proof of concepts are numerous- natural leather synthesized from yeast, bioconcrete which contains bacteria capable of repairing damage over time (Seifan et al. 2016), and bioluminescent lamps to create light without electricity (Myers 2012). Long-term biodesign architectural structures have also been constructed. For example, the Living Bridge in Meghalaya, India (Ludwig et al. 2019) and the B.I.Q. House in Hamburg, Germany, are the first algal-powered buildings (Chang et al. 2017; Myers and Antonelli 2018).

Biodesign often lacks the efficiency of biomimicry, yet biomimicry itself is not inherently sustainable. Researchers have thus called for integrating both approaches in architectural structures (Andréen and Goidea 2022), necessitating a hybrid 'biological design' framework. An example of this synthesis is 'Living Mushtari' (Bader et al. 2016). Designed for space wear, it employs 3D-printed channels mimicking intestinal peristalsis to move cyanobacteria (biomimicry), while its embedded synthetic microorganisms harness sunlight to produce useful outputs like pigments or food (biodesign). Similar 'Wanderers' structures further demonstrate this potential (Song 2021). This paper defines 'biological design' as this integrated problem-solving approach. By combining biomimicry's efficiency with biodesign's sustainability, biological design serves as a 'poster child' for Life-centered design.

2. Emphasis on United Nations Sustainable Development Goals and Design Education

While educators have explored biomimetic applications in design education (Santulli and Langella 2011; Qureshi 2022; Coban and Coştu 2023; Fried et al. 2020), biological design remains underutilized as a teaching strategy for sustainability. This paper proposes a biological design framework to teach U.N. Sustainable Development Goal (SDG) problem-solving. Established in 2015, the 17 SDGs target 2030 solutions (Kleespies and Dierkes 2022). Because these goals are highly interdependent (Song and Jang 2023; Laumann et al. 2022), adopting biological design strategies is imperative.

This report explores integrating biological design into Life-centered design education. As sustainability requires collaboration across social sciences, biology, chemistry, and engineering, such interdisciplinary courses provide a crucial training ground. Establishing biological design as a Life-centered strategy within academic curricula is therefore vital before students enter the professional workforce.

3. Biological Design as a Project-Driven Course in a Liberal Arts Educational System

Course rationale: The honors program at Simpson College (SC) follows an interdisciplinary curriculum. The SC 101 Honors course, "From Cells to Palaces", was created to assist students in understanding the field of biological design and, using this as a problem-solving strategy for a multitude of issues that we face as a society. The United Nations' Sustainable Development Goals (Table 1) were used as a benchmark in the course. The 2030 Agenda for Sustainable Development was adopted by U.N. members in 2015. The seventeen goals addressed call for urgent action by all countries to work to improve the lives of people, the sustainability of the planet, and to achieve prosperity. Through this course, students were taught to use inspiration and ideas from biology that they could apply to challenges and design products, allowing for sustainable use in the real world.

Table 1: UN SDG Goals listed at https://sdgs.un.org/goals

U.N. Sustainable Development Goals		
1 No Poverty	7 Affordable and Clean Energy	13 Climate Action
2 Zero Hunger	8 Decent Work and Economic Growth	14 Life Below Water
3 Good Health and Well-being	9 Industry, Innovation and Infrastructure	15 Life on Land
4 Quality Education	10 Reduced Inequalities	16 Peace, Justice and Strong Institutions
5 Gender Equality	11 Sustainable Cities and Communities	17 Partnership for the Goals
6 Clean Water and Sanitation	12 Responsible Consumption and Production	

The course design and student learning objectives are listed in Figure 1 and Figure 2 respectively. This course was set up in two parts. The first half of the semester introduced students to the concepts of biomimicry and biodesign. Students' understanding was assessed using in-class activities and mini projects to address a specific global problem assigned by the instructor. The entire class worked on models to solve the issue. During the second half of the semester, students were presented with ample information regarding the 2030 Agenda for Sustainable Development adopted by U.N. members in 2015. Students were assigned to smaller groups and worked as a team to identify a topic of their interest. Students then used the resources presented to pick specific categories to design solutions for a real-world issue that piqued their curiosity. A significant part of the project work was based on research pertaining to the field of sustainability. Apart from the literature review, students created novel designs for their final projects and presented them to the class. Video presentations were also encouraged.

Course design: The overarching goals of this course were to bring to the forefront:

a) The significance and urgency of finding solutions from biology for a sustainable lifestyle.
b) Combining both biomimicry and biodesign in product development to enhance life-centered design learning.

To address these goals, students learned theoretical concepts centered on the following four units covering (broadly) the categories of biological design listed below:

1. Use of biological design and concepts for architecture and living spaces.
2. Use of biological design and concepts for product design.
3. Use of biological design and concepts for processes.
4. Sustainability in biology and its implementation in our societies and economy.

Figure 1: Course Design

Assessment: This course was dependent on a liberal arts approach to problem-solving. It taught students how to attempt to manage an issue by drawing ideas from various disciplines through regular assignments, discussions, and presentations. This training eventually helped them design their final class project, a model developed by each group during the second half of the semester, based on biomimetic and design principles, and doing a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis (Table 2). This paper serves as a case study to inculcate interdisciplinary thinking amongst students in the field of sustainable studies. Future work will focus on the research process and pedagogical analysis of this study.

Student Learning Objectives (SLOs) for this Course:

S.L.O. 1: Successful SC Honors students will demonstrate the influence of the liberal arts in their life *perspectives and projects*

S.L.O. 2: Successful SC Honors students will be able to recognize and apply multiple disciplinary approaches to analyzing and solving a problem rooted in the traditional liberal arts and sciences. The implementation of the above objectives was carried out by ensuring that students in this course learned the following:

1. Form and function in biology and how these were useful to the organism/systems. Ultimately, the goal was to help students understand the importance and the 'ease' with which nature ensures sustainability. They, in turn, converted these concepts into products for use by individuals or communities (an article of use or a dwelling).
2. The importance of a circular economy (an economic system aimed at eliminating waste and the continual use of resources). They used their understanding of sustainability in biology (from the first SLO) and applied these concepts for implementation in our economy.
3. An understanding of life-centered design thinking. How does a society consider the core needs of a person/group experiencing a problem? How does a society ensure that the issues associated with these solutions are also environmentally non-invasive? Students confirmed the environmental issues they addressed from a biomimetic and Biodesign perspective in their models. The term life-centered design was not used during the course. Instead, the phrase 'human-centered with a sustainability focus' was discussed throughout the course.
4. Worked collaboratively to address complex issues of the U.N. sustainable goals keeping in mind the principles of Life-centered design.
5. Honed their communication skills through presentations and discussions on their design ideas.
6. Developed critical thinking ability during collection, assimilating, and interpreting information required to address issues related to sustainability.

Figure 2: This course fulfilled the above Student Learning Objectives (S.L.O.) of the honors program at SC.

4. Design Analysis and Discussion

Final project outcomes: During the semester, students carried out mini projects based on one or more of the following: 1) designing architectural spaces, 2) designing processes, 3) designing products, 4) finding innovative solutions to existing problems, such as 'saving Venice from sinking.' The initial implementation was slow as students spent time learning the general concepts and the differentiation between biomimicry and Biodesign. After some initial frustrations, as the smaller projects were getting developed, project-specific input and analysis helped students understand how biomimicry and Biodesign differ from each other, and they were able to put together how both these concepts corresponded to biological design.

General trends: Since this course was interdisciplinary, it was essential to ensure that in addition to biology and design, students focused on other aspects of the product they were creating, such as the seriousness of the issue, immediate need, understanding of the targeted population, etc. Additionally, it was important for students to recognize that they were developing products for real-world applications. One of the sections that was the focus of this course was a SWOT analysis; a tool used in business to assess the competition that organizations face. The elements addressed by students are listed in Table 2.

Table 2: Prompts provided for the final class project.

Component	Description
Problem	What is the UN sustainable development goal theme that you chose?
	What is the problem/environmental issue at hand corresponding to this goal?
	What are the present solutions? Do they work? If not, why?
	Give a brief description of the relevance of your design
Design	Is your design biomimetic? Please explain.
	Is your design based on the principles of biological design? Please explain.
	Please explain the biomimetic and bio-design components of your design.
	How is your design made sustainable? Please involve all aspects of sustainable design in your element.
	Include a detailed, labeled diagram or flow chart of your design. Please also include a figure legend. Address the design elements in your writing.
SWOT	What are the strengths of your design?
	What are the weaknesses of your design?
	What opportunities are available to implement or promote your design? For example (but certainly not limited to) geographical areas.
	What are the threats involved in your design?
	What is the competition to your design?

Of the four group projects, two focused on U.N. sustainability goal #14, Life Below Water, two other groups selected goal #11-Sustainable Cities and Communities, and one team chose #4, Quality Education. All the groups had a sound rationale for choosing their topics, primarily focused on the urgency of environmental goals that needed to be addressed. One group did not pick an ecological issue but instead addressed a societal problem, focusing on a significant restructuring of the educational system in the U.S. Interestingly, two of the groups that chose Life Below Water as the challenge to be addressed zoned in on getting rid of microplastics from the oceans. The other two groups that selected Sustainable Cities and Communities as their U.N. sustainable goal chose very different problems to address: 1) reducing environmental carbon emissions and 2) constructing sustainable buildings. Four of the five groups listed in Table 3 used biomimicry and design concepts in their product design. Interestingly, the group that did not use a biodesign element developed a novel approach, termed 'Animal learning,' to improve the U.S. education system based on mimicry of animal learning patterns across species. Since no tangible product was created, they could not use biodesign elements in their project. This design was a novel approach, proving that student understanding of design involving natural systems is more comprehensive than just products, buildings, or spaces. Biological design transcends physical limits and has a place in conceptual systems.

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While design inspirations varied, most groups prioritized animal models. Notably, only one team utilized plants, specifically ginkgo leaf microstructure. This trend likely stemmed from the need for locomotion in mobile products like 'SHRIMF' and 'Plastic Munchin,' both ocean-based microplastic collectors. Despite targeting identical issues, these teams drew from distinct biological inspirations: 'Plastic Munchin' mimicked suspension feeder locomotion (Figure 3A-D), whereas SHRIMF utilized shrimp and bovine stomach models (Figure 3E).

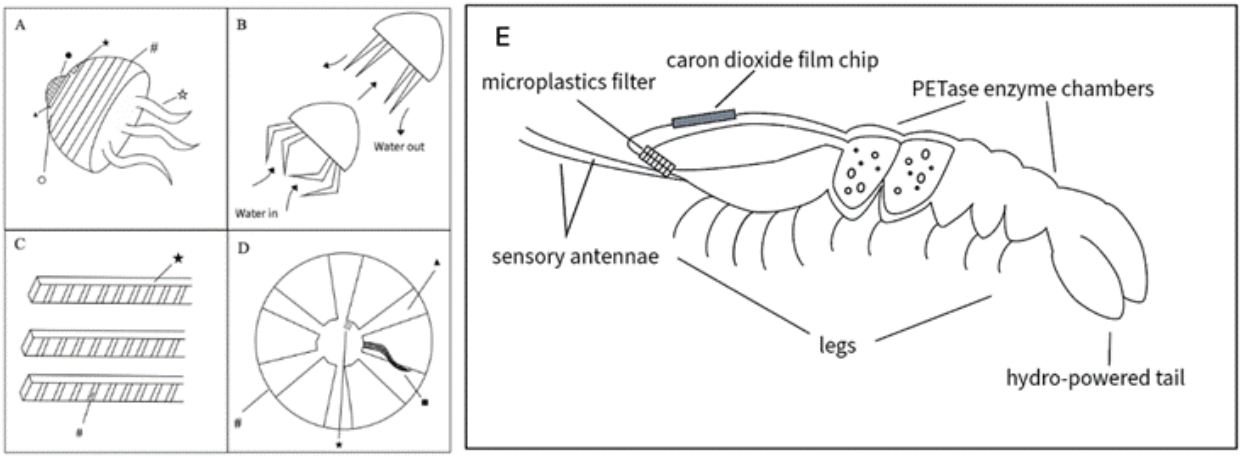


Figure 3: A) Design of the 'Plastic Munchin,' a biodesign and biomimetic microplastic-removal device. (A) The jellyfish-inspired fiberglass structure is coated in mucopolysaccharide to facilitate movement. (B) Locomotion mimics biological systems: tentacles expand to intake water and contract to propel the device forward. (C) Grooved body segments house engineered Ideonella sakaiensis, which secrete PETase to degrade polyethylene terephthalate (PET) into absorbable carbon sources. (D) The apex panel filters larger debris, while collection tubes funnel microplastics into a central chamber. An integrated satellite-linked sensor monitors capacity and system status, triggering alerts for maintenance or potential entanglement. To ensure environmental safety, the device features a mechanism to release pardaxin, repelling predators without causing harm. E): Design concept for Sustainable Hydro Roomba Independent Microplastics Fisher (SHRIMF). The device is made of syntactic metal foam, which allows it to withstand pressure in ocean depths. The product is two feet long. A film chip aids in using carbon dioxide and sunlight to power the movement of the device. A series of 'legs' help in forward movement. The tail helps in vertical movement, allowing the machine to travel up to the surface to collect sunlight and carbon dioxide. Once the collection is complete, the tail propels the device to move into the ocean to collect microplastics. Sensory antennae help communicate with a program on land to provide information regarding the power level, microplastic intake, malfunctions, etc. The digestion of microplastics takes place inside the 'abdomen' of the device in enzyme chambers. These chambers contain PETase, which helps in the enzymatic degradation of polyethylene terephthalate (PET).

All projects, excluding the education-focused group, incorporated multiple biomimetic and biodesign elements. Initially, students struggled to differentiate biophilic design from biodesign, often conflating the latter with merely sustainable materials. However, they ultimately integrated natural elements effectively. Four of the five projects (Table 3) featured novel inspirations; even when utilizing existing compounds, students applied them uniquely. Despite one group requiring supplementary guidance, 80% of the class successfully generated original concepts, satisfying the assessment and Student Learning Objectives (S.L.O.s). Students also performed SWOT (Strengths, Weaknesses, Opportunities, and Threats) analyses to assess project viability. While these analyses

provided a sound evaluation framework, they often neglected design longevity and end-of-life fates for natural components. This oversight was significant, as many biodesign elements whether living organisms or biological products could become toxic if accumulated excessively. Notably, the 'Plastic Munchin' group (Figure 3A-D) recognized this, proposing a lab-synthesized mucopolysaccharide that mimicked suspension feeder mucus to facilitate movement. However, their design failed to account for the biological reality that natural suspension feeder mucus requires continuous tissue-level renewal for sustained efficacy.

Table 3: A list of final projects designed by students in the SC 101, Honors: Biological design-from cells to palaces, course.

Project name	Problem	Biomimetic inspiration / biological design	Characteristic features
SHRIMF (Sustainable Hydropower Roomba Independent Microscopic Fish(er))	Microplastics in the ocean	Shrimp and cow stomach	1. Antennae of shrimp as a form of communication 2. Shrimp tail for movement 3. Stomach chambers of a cow for digestion 4. CO_2 film chip as an energy source 5. PETase enzyme chamber (Chen et al. 2022)
Plastic Munchin	Waste in oceans	Suspension feeders, specifically jellyfish and mucus-mesh grazers	1. Tentacles of the jellyfish for movement 2. Mucopolysaccharides from suspension feeders for movement of water 3. Bacteria *Ideonella sakaiensis* for decomposition
On the Ginkgo	Air pollution	Ginkgo leaves and cyanobacteria	1. Cyanobacteria for fixing atmospheric nitrogen and absorbing carbon dioxide 2. Anatomical structure of the ginkgo leaf waxy cuticle
Animal Learning	Western centric, non-diverse model of education in the U.S.	Elephants, meerkats, zebra finches, sperm whales, cheetahs, and chimpanzees	1. Observation application as followed by elephants and meerkats 2. Trial and error method of learning by meerkats, cheetahs, and zebra finches 3. Skill based progress followed by killer whales, cheetahs, and meerkats 4. Group learning followed by elephants, chimpanzees, and sperm whales
The Ultimate Sustainable Building	Unsustainable buildings	Microbial composting, wind powered air filtration and BCSA cement, Refish®	1. Refish® design (based on gills of a fish for filtration) 2. Bacteria in 'living concrete' helps solidify cement 3. Bacteria in compost helps break down organic matter to produce heat

4.1 An Introduction to Observational Digestion

Observational digestion is proposed as a reflective process for interpreting biological and bio-inspired artifacts, including their physical characteristics, associated data, metadata, and cultural and environmental contexts. It considers how information is perceived, registered, or interpreted by living organisms, human observers, and engineered systems without necessarily attributing cognition to non-living entities. Debates concerning adaptive capacity and organismal cognition complicate conventional definitions of life (Smith, 2018; Cazalis et al., 2017). Kinetic artworks and self-organizing colloids demonstrate life-like behaviors without establishing biological life (Jansen, 2008; Palacci et al., 2013), while ethical questions surrounding digital replicas further distinguish representation from living identity (Häyry and Sukenick, 2025). Such interpretations also benefit from culturally situated perspectives on observation and knowledge (Gabrielsen et al., 2017).

Engineered materials similarly expand the scope of observation. Foundational metamaterial research (Kshetrimayum, 2005; Engheta and Ziolkowski, 2006; Cui et al., 2010; Liu and Zhang, 2011) and subsequent developments in digital, programmable, and functional materials (Della Giovampaola and Engheta, 2014; Cui et al., 2014; Zheludev and Kivshar, 2012; Kadic et al., 2019; Valipour et al., 2022) demonstrate how material behavior may depend on engineered structure rather than outward appearance. Under the proposed approach, observing a hypothetical tissue-engineered wallet would involve evaluating its sensory properties alongside documented biological origins, production history, and ecological implications. Such information may require external documentation rather than being recoverable from the artifact itself, reinforcing the importance of contextualizing biological data (Leonelli, 2016).

This interpretive scope also encompasses computational applications of biological principles, including bio-inspired algorithms and DNA-inspired encryption (Somvanshi et al., 2025; Abdelaal et al., 2025), alongside synthetic biology education and DNA-origami fabrication (Kuldell et al., 2015; Bush et al., 2020). Informed by multispecies information science (Solhjoo et al., 2023) and life-centered design (Borthwick et al., 2022), observational digestion connects biological observation with reflective, context-sensitive, and preferably non-invasive inquiry. Within the course, it represents a proposed interpretive extension rather than an explicitly taught or empirically validated methodology, encouraging consideration of environmental consequences and, where applicable, cyberbiosecurity responsibilities (Potter and Palmer, 2023).

Ethical and Security Considerations in Biological Design: Biologically inspired design warrants interdisciplinary scrutiny, particularly where biological and digital systems intersect (Peccoud et al., 2018; Elgabry and Johnson, 2024). Demonstrated vulnerabilities involving malicious DNA-derived inputs (Ney et al., 2017) and manipulated medical images (Mirsky et al., 2019) illustrate distinct security concerns. These underscore the importance of data integrity, contextual interpretation, and validation in data-intensive biomedical research (Leonelli, 2024). Ethical considerations also extend to privacy, consent, and care in information exchange (Wittkower, 2016a), alongside preventing exclusionary or discriminatory outcomes in technological design (Wittkower, 2016b). The 2025 Spirit of Asilomar entreaties further propose approaches to risk assessment, governance, environmental stewardship, and inclusive biotechnology education (Hodgson et al., 2025; Abbott et al., 2025; Chemla et al., 2025; Flores et al., 2025; Zimmerman et al., 2025; Jannah et al., 2025). Building on the preceding discussion, observational digestion is proposed as a reflective approach to interpreting biological and bio-inspired artifacts, their associated data and metadata, and their cultural and environmental implications, rather than as an explicitly taught or established methodology.

Experiential learning was at the core of this course. Students were problem-solving for sustainable solutions, familiarizing themselves with multiple fields of study. They developed an understanding of research, experimentation, reflection on their product, application of their product, economics, and, most importantly, the necessity to convert an abstract idea into a tangible output. Students developed an understanding of the intricacies and interdisciplinarity of biological design at the core. This course balanced a theoretical understanding of biological design and practical immersion via inquiry-driven study that was important for problem-solving. Therefore, this course will be a stepwise transition into more extensive and more hands-on experiences such as modeling competitions, workshops, research projects, etc.

Ethics Declaration

This study does not use human subjects. Therefore, ethical approval through IRB is not applicable.

AI Declaration

AI tools were not used in the development of source material. Those within Google Docs and Grammarly were used for organizing such.

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