Using Structures, Functions, and Mechanisms to Access Biological Analogies: Experiences from High School Engineering Teachers' Professional Development

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2021 IEEE Frontiers in Education Conference (FIE) | 978-1-6654-3851-3/21/$31.00 ©2021 IEEE | DOI: 10.1109/FIE49875.2021.9637291

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***Abstract*—This innovative practice work in progress paper presents Biologically inspired design (BID) to transfer design principles identified in nature to human-centered design problems. The Biologically Inspired Design for Engineering Education (BIRDEE) program uses biologically inspired design to teach high school engineering in a way that uniquely engages students in the natural world. For high school students, identifying natural systems' analogues for human design problems can be challenging. Furthermore, it is often the case that students focus on and transfer superficial structures, rather than underlying design principles. Based on the Structure-Behavior-Function (SBF) design ontology, we developed a modified cognitive scaffold called Structure- Function-Mechanism (SFM) to assist students and teachers with identifying functionally similar biological analogies and identifying and transferring design principles. In this paper we describe SFM and its importance in BID and our observations from teaching SFM to high school teachers during a multi-week professional development workshop in the summer of 2020. Based on teachers' work artifacts, transcriptions of discussions, and focus groups, we highlight the challenges of teaching SFM and our plans to scaffold this important concept for students and teachers alike.**

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

I. INTRODUCTION

Over 3.8 billion years, the process of evolution has produced innumerable problem-solving strategies. Whereas human solutions tend to apply energy and monolithic materials, biology leverages information, abundant local resources and structural relationships [1]. Famously, George de Mestral invented Velcro through the careful observation of the hook-and-loop design of burs as they stuck to the fur of his dog [2, 3]. Likewise, the Wright brothers, by observing soaring buzzards, invented wing deformation features to assist with aircraft maneuvering. NSF's Big Idea challenges seek to discover and understand such biological strategies, or "rules of life," and Biologically Inspired Design (BID) leverages these strategies to develop solutions that engage meaningfully in the broader biological world. BID helps people to develop curiosity for, and to see value in, understanding the biological world that surrounds them.

In the BID examples provided above, biology served as a serendipitous inspiration for a technical or engineering problem. However, to teach BID, we require reliable, systematic methods for finding and applying biology to design problems. In addition, the emphasis on biological solutions, which can be highly engaging and intriguing to designers, often results in single- solution fixation. Jumping to a solution too quickly or fixating on a solution is generally considered poor design thinking [4, 5].

The Center for Biologically Inspired Design (CBID) at Georgia Tech developed a pedagogical framework for teaching BID [6-8] aimed at teaching senior-level college students. The goal of the Biologically Inspired Design for Engineering Education (BIRDEE) project is to develop modules for 3 high school engineering classes grounded in BID, making BID accessible to high school engineering teachers and students. We contend that incorporating BID-learning into high school engineering courses will promote broader participation in engineering as a field of study.

This material is based upon work supported by the National Science Foundation under Grant No. #1907906. 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.

To enable high school students and engineering teachers to search for relevant biological analogies for engineering design problems, we developed a cognitive scaffold called Structure- Function-Mechanism (SFM). These descriptors provide a language and structure for systematically reverse engineering systems, both man-made and biological, to understand how they work. The framework facilitates analogical search using functional indexing, distinction of structure from mechanism, and the transfer of principles rather than structure from biology to engineering. SFM is based on the Structure-Behavior- Function (SBF) design ontology [9] but is adapted to fit the needs of high-school engineering students and teachers.

In this paper, we briefly describe SFM and reflect on teaching SFM to high school teachers during summer professional learning (PL). We provide examples of SFM activities from the PL and discuss how lessons learned from the PL are informing the design of curricular activities around SFM to scaffold these key ideas for high school engineering students.

II. STURCTURE, FUNCTION, MECHANISM

Structure-Behavior-Function (SBF) is a design ontology that describes how interactions among structural elements give rise to functions. In prior work, the SBF vocabulary was introduced to an interdisciplinary group of undergraduate students as a language for describing both engineered and natural systems [10]. It was found that the common vocabulary is useful for students in articulating how a system works, especially for systems outside of their domain of expertise.

The SFM framework is designed to help students avoid what we call the "hairy house" problem [11], where a novice BID student might design a house that stays warm by placing polar bear fur on its outside. Rather than purely structure transfer, the goal of BID is to learn from the underlying principles that we already know are effective from biology, and implement those principles using materials and designs that are appropriate for engineered systems. In this case, we want the student to understand that polar bear fur insulates the bear by creating an air boundary with low thermal conductivity, effectively reducing heat transfer from the bear's body into the cold air, and to transfer the air boundary principle using appropriate materials.

The Next Generation Science Standards (NGSS) include Function-Structure as a cross-cutting concept. The SFM framework meaningfully wraps NGSS cross-cutting concepts around the existing SBF ontology for application in engineering. The goal of BIRDEE with respect to SFM is to develop fluency in describing systems using these categories and to teach students how to transfer mechanisms, rather than structure. As a framework for systematically understanding engineered systems, we believe SFM may be applicable in more than just the BID context.

A. Structure

The structure of a system is the most easily identifiable component of the SFM framework as it is generally tangible and frequently visible. A structure could include a veining pattern

on a leaf, a serrated edge on a leaf, an animal's feature, such as a mane on a lion, a sharp tooth, etc. In engineered systems, structures could include a pipe, pipe fittings, a hinge, a bracket, an actuator, etc. While structures could be chemical or invisible to the naked eye, students tend to focus on visible components when learning the SFM framework. Sketching activities can help students focus on and find meaningful structures and develop curiosity about why it is the way it is.

B. Function

The function of a system is the second-most intuitive component of the SFM framework. The function is the action a system takes to effect change in the world (or in some cases to prevent change, such as a lock preventing a door from opening). Whereas structures are nouns, functions always include verbs. In engineering design, development of function trees describing the tasks a device or system must perform [12] and/or performing a functional decomposition [13] is relatively commonplace. For biological systems, it can be challenging to infer a function from a structure, particularly when it is taken out of context. For example, it is not readily obvious that a leaf may manage water internally and externally in some novel way unless a student has some hint to study that possibility. It is sometimes easier to determine functions with fauna that move and interact with their environments in highly observable ways; on the other hand, the functions can be complex and interrelated. For example, an elephant's trunk can perform several different functions.

C. Mechanism

The mechanism is the interaction of components and technical principles that enable the function to occur. For example, in the "hairy house" polar bear-inspired scenario described previously, the mechanism is the air gap created by the fur that reduces conductive heat transfer. Another example is the super hydrophobic behavior of a lotus leaf that is created by tiny nanostructures that cause water to bead up from the surface by altering the contact angle between the water and surface.

The mechanism is generally the most challenging component of the SFM framework for students as it is not readily visible and requires knowledge of the underlying technical principles. Even though the mechanism may be the most confusing element of the framework, it is arguably the most important for two reasons. The first is that transfer of mechanism allows for contextualized adaptation of the mechanism from biology to the engineered world, to meet the needs of the human problem, which will be different than the biological problem. The second reason for focusing on mechanism is that age-appropriate scientific and mathematical models can be introduced to show how math, science, and engineering are meaningfully integrated. This is also a key component of authentic engineering practice.

III. Teacher Professional Learning

Description: Several Professional Learning (PL) activities were designed to introduce teachers to SFM during first year of the BIRDEE project (Summer 2020). Note that the project began in fall of 2019, so almost a full year of curriculum development

had taken place and the team knew that SFM was a cornerstone of the BIRDEE units. The PL happened in six weeks during the summer of 2020. Given the global pandemic, all activities happened virtual and remotely. During the six-week summer PL, we used different approaches to teach SFM analysis to teachers: (1) presenting SFM; (2) conducting SFM analysis on biological objects; and (3) relating SFM analysis to engineered objects. For basically all PL activities, teachers were acting as students; that is, we wanted the teachers to experience these activities as learners and put aside pedagogical approaches. While pedagogy naturally came up sometimes in conversation, we tried to allow the teachers to experience the activities as students without the complexities or concerns around classroom management or perceived pedagogical challenges.

Participants: Four teachers participated in this round of PL. Teachers were diverse in terms of gender, two female and two male, racial background (two white and two Black), teaching experiences ranged from 1-11 years, and prior engineering training. All came from low-socioeconomic school districts. All teachers participated in the entire six-week PL.

Data Collection Methods: We recorded all the video- conference calls to capture teachers' discussion around the activities. We also saved all their responses to the assignments. Additionally, we conducted a focus group with all four teachers, with semi-structured questions. We recorded teachers' conversation.

Preliminary Findings: While we have not fully analyzed all the data, below we share some preliminary findings about the SFM activities. We first describe the activities, and then share briefly what teachers learned and did during these activities

A. What is SFM?

We first introduced teachers to SFM through definitions, explanations and examples. In the kickoff session for the summer, which was entirely virtual due to COVID-19, we discussed BID and its contributions to engineering. We also presented explanations of SFM though some examples. Definitions were given at the beginning of the relevant activities. Some of the definitions developed organically, during conversations with teachers to better explain them in student- level terminology. An example of a definition that was given to teachers is:

"Informally, a **mechanism** is: Something [**structure**] does something to something to accomplish something [**function**]. More formally: *A mechanism is the interaction between structures and substances (material, energy, information) that gives rise to the function*."

At the time, many of the BIRDEE team members were also new to SFM, so we were still finding the right definitions. We continue to work on developing the SFM lexicon, definitions and tools that are appropriate for high school engineering teachers, and ultimately, for students.

Findings. In this session, teachers discussed ways they had used SFM in their assignments, and ways they can use these concepts in future. One teacher shared that her students usually miss paying attention to details and how things around them work. She said introducing these concepts could help them focus

Fig. 1. Found object sketch and hypothesized function examples

on components of a system and mechanism it takes the system to serve a goal. Overall, teachers seemed to find value in SFM while simultaneously struggling to both perform the analysis and having some concerns about students' abilities to perform the analyses.

B. *Examining Biology*

We structured opportunities for teachers to practice SFM on biological objects. In two of the activities, teachers were encouraged to go into nature and explore. In the first activity, called Found Object, teachers were asked to identify an object from nature with an interesting function. They were given the hint that "a function is a verb, e.g. disperse seeds, reduce drag for certain leaves, jump for a grasshopper". They were asked to analyze the object they found and describe its function by (1) Sketching the object, (2) Annotating the object, and (3) Describing (or speculating about) how key features give rise to the function of interest.

Findings. In this activity, teachers explored and discussed different natural objects such as spikes on a seed pod, poison ivy, leaves and insects. They were able identify the components of natural objects (structure) and hypothesize their functions. In Figure 1 we see two of the teacher sketches and their explanation of function. Generally, the mechanism explanations were lacking or contained misconceptions.

C. *Bringing Biology to Engineering*

In a second activity, teachers were prompted to virtually visit a zoo, an aquarium, or a botanical garden and observe different organisms. The teachers documented any interesting functions the organisms performed, the structures they used to perform those functions, and applicable mechanisms. They were additionally asked to suggest how the organism might serve as an inspiration for human engineering problems.

Organism	Biome	Activity	Function	Mechanism	Differences	Eng Target
Platypus	transitional woodland	swimming	mobility	front limbs rotate in a circular motion	Most ships use propellers, fixed in place, but using a similar rotational motion	efficient submersibles for surveying and exploration
Meerkat	Arid	Standing and	Sensing	Balance on two legs, mechanisms	Human systems	Create systems different function
Hippopotamus	Tropical	Submerging almost	Cooling and	Combination of motion	Submarines must	Aquatic /

Fig. 2. Example assignment for zoo observation protocol

Findings. This activity helped teachers not only practice

regarding their experiences, describing this mostly as a new , but very useful concept for learning engineering design for their students.

"*The investigation portion was fun in that it really caused me to think about what I was actually looking for and some of the different functions of the insect, plants and etc.. that are around me.*"

"*My students can examine the solutions, the parts and structure, what they do like function, and mechanism that you're asked.*"

"*Yeah, separating form from function. Separating structure from mechanism was really helpful to and I think could be really*

SFM analysis on various natural objects, but also to begin thinking about BID, and how these objects (or biological systems) can be used in engineering. Figure 2 provides an example of the assignment. In general, we found that teachers had an easier time finding functions for animals that were moving around (at the zoo), as opposed to the found objects which could be taken out of context. That is, a leaf's functions are not readily apparent or directly observable. Therefore, it may be easier to scaffold this activity by steering students and teachers to animals first.

D. Integrating SFM into Engineering Design

Early on in the PL unit, teachers received an engineering problem statement. The statement covered possible difficulties of shipping and transporting of vaccines and other medicines to remote places, especially overseas, given the challenges of maintaining appropriate temperatures and preventing damage to the shipping containers. That is, there were two functions— thermal insulation, and impact resistance, that had to be considered in the design of the vaccine shipping containers, in addition to other constraints such as the size of the vial. Teachers were provided structured activities that took them through the engineering design process to ultimately develop a prototype solution, while considering BID. We specifically designed the engineering problem to include insulation—a function that has many biological analogues that would be easy for teachers to find and consider in developing their designs.

Findings. We observed that even though teachers were not asked to think about SFM specifically in these engineering design activities, some of them adopted SFM at different stages of design. For example, as they were planning for their low- fidelity prototyping, they broke down the parts and discussed function, structure and mechanism of each part. Two examples are provided in Figure 3. In these particular examples, the biological connections may not be clear; the purpose of this figure is to show the adoption of the SFM framework and vocabulary, not the overall BID process. The only evidence of BID in these particular examples is the goal of creating air pockets, which is a thermal insulation technique used widely in nature (e.g. in polar bear fur.)

IV. Teachers' SFM Knowledge and Reflections

At the end of the PL, we conducted a focus group with teachers, asking them about what they learned. With respect to SFM specifically, teachers provided more explanations

effective in the classroom. Help students understand the objects around them a lot more deeply."

"With SFM. I also really like that because I've kind of always thought a little bit in those terms, but I didn't have it as concrete…Identify all of the structures on this thing that you think have a purpose and what that purpose is. And given the framework of SFM, I feel like I could apply that to that lesson and kind of teach them both about the intentional design elements as well as that structure. So I think that was also very valuable."

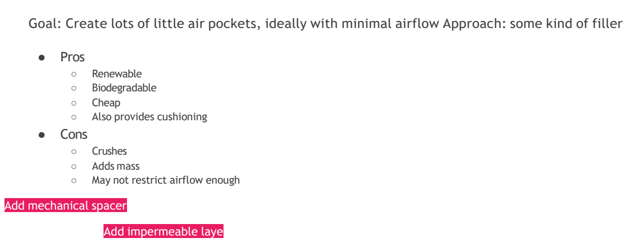

Fig. 3. Low fidelity prototype descriptions containing SFM language

They also suggested that it remained confusing for them:

"The SFM or whatever. I liked learning about that. I mean, that for me was an example of how we all turned in different

things. I didn't feel like we understood [it] clearly… I still felt like I have a lot to understand about it." "…SFM, I'm still struggling with that."

"For all of us, we probably could've stopped and just taken a week just to learn SFM. Just to learn that portion. Just to learn how to do it right. So when we're in the classroom implementing it, we will have to I'm sure stop and re-teach some concepts."

V. Conclusions and Future Work

The concept of structure-function-mechanism (SFM) is introduced in this paper as a core tenet for teaching biologically inspired design (BID). Based on what we observed from teachers' engagement with SFM and their reflections on how to use SFM in their engineering classes, we believe SFM provides a common vocabulary across engineering and biology, and a framework to begin understanding how and why systems work the way they do. SFM is also grounded in NGSS structure- function, providing additional reinforcement for this model of accessing biological analogies. Perhaps most importantly, functions provide a window between the engineered and biological worlds, a place to search for biological analogies. Meaningful transfer occurs when we can understand the structures, but apply the mechanisms. The mechanism of why something works, the scientific explanation, is what allows for meaningful BID to take place, but it is the mechanisms that can be the hardest part to determine correctly without sufficient experience in analyzing biological systems.

Based on insights from the first teacher professional learning workshop in 2020, SFM provides teachers with a framework that may be useful for understanding and describing complex systems and designs and for teaching BID. However, SFM is difficult to explain and will likely require significant scaffolding in the BIRDEE curriculum units. Based on teachers' observations and misconceptions, student materials are being developed to scaffold this learning across the three BIRDEE units. We will initially constrain the functions and provide biological examples for inspiration where the mechanisms can be clearly modeled and described.

In future work, we will be implementing the BIRDEE units with a significant focus on SFM and collecting student and teacher data regarding the efficacy of this curriculum as well as impacts on teaching and learning. We will iterate and update the curriculum after the first year of implementation in 2021- 22.

ACKNOWLEDGMENT

The BIRDEE team would like to acknowledge Michael Ryan for his contributions to the ideas put forth in this paper.

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