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GETTING BEYOND THE HAIRY HOUSE: USING STRUCTURE-FUNCTION-MECHANISM TO ADVANCE BIOLOGICALLY INSPIRED DESIGN PEDAGOGY

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ABSTRACT

In this case study we report on the use of a Next Generation Science Standards (NGSS)-aligned form of Structure-Behavior-Function, called Structure-Function-Mechanism (SFM), to teach four high school engineering teachers an approach for Biologically Inspired Design (BID). Functional theories of design describe a natural way in which designers solve design problems. They provide support for case-based and analogical-based reasoning systems and have been used successfully to teach BID to undergraduate students. We found that teachers instructed on BID practice and pedagogy using our modified theory were able to grasp the structural concepts and looked for clear markers separating mechanism (behavior) and function. Because of the systems-of-systems nature of most biological entities, these boundaries were often subjective, presenting unique challenge to teachers. As high school engineering teachers look for methods to enhance their pedagogy and to understand multidisciplinary content, these findings will inform future curriculum development and professional learning approaches for engineering education.

Keywords: biologically inspired design, engineering education, teacher training, SBF

1. INTRODUCTION AND BACKGROUND

In this study we report on the use of a Next Generation Science Standards (NGSS)-aligned form of Structure-Behavior-Function (SBF), that we call Structure-Function-Mechanism (SFM), to teach four high school engineering teachers an approach for Biologically Inspired Design (BID). Functional theories of design, such as SBF provide an ontology for describing how designers analyze and synthesize a designed system [1] and provide support for intelligent case-based and analogical based reasoning systems [2-4]. SBF also has been used to teach middle school science, [5], and BID to undergraduate students [6, 7]. We modified SBF to serve as a framework for instructing high school teachers and BID practice and pedagogy as part of a novel course that we are developing for high school engineering education.

The goal of the Biologically Inspired Design for Engineering Education (BIRDEE) project is to develop modules for 3 high school engineering classes that are grounded in BID. The hypothesis is that because biological sciences and bioengineering attract women at higher rates [8], the infusion of BID into engineering classes that evolved out of woodshop [9], may increase enrollment and retention of high school women, who typically enroll in these courses at very low rates [10]. In addition to BID content, the courses feature human-centered design contexts highlighting the humanistic side of engineering [11].

Because of the multidisciplinary and analogical nature of BID, guidance is required for both students and teachers to effectively look to biology for inspiration and functional solutions to engineering design problems. The need for a clear, understandable process of accessing and evaluating biological analogies requires SBF to be a fundamental learning goal for the curricula. Specifically, teachers and students will need to be able to describe the function(s) that an engineered or biological system executes (Function), the Structure that allows that function to occur, and the Mechanism, or fundamental principle that makes the structure effective, e.g., an elephant's ear can be fanned out, away from its body (structure) to stay cool (function) using convective heat transfer(mechanism), like fins on a radiator.

2. MATERIALS AND METHODS

2.1 Participants

Four teachers participated in the BIRDEE teacher professional learning (PL) in the summer of 2020. Teacher 1 was a male engineering teacher with a bachelor's degree in computer science. He had one year of high school engineering teaching experience, and five years overall as a teacher in grades 1-12. Teacher 2 was a female teacher with 11 years of experience teaching high school engineering. She had a master's degree in technology education, and previous working experience in a corporate engineering and technology department for 13 years. Teachers 1 and 2 taught at different high schools in the same district. Teacher 3 was a female teacher with 2 years of experience in teaching engineering in high school. She received her bachelor's degree in mechanical engineering and a master's degree in material science and engineering. She had previous biomimicry research experience during her masters. Teacher 4 was a male with 1 year of experience in high school engineering teaching. He received his doctoral degree in electrical and computer engineering. Teacher 3 and Teacher 4 taught at the same high school.

2.2 Structure-Function-Mechanism (SFM)

Structure-Behavior-Function (SBF) [1] is a design ontology that describes how interactions among structures give rise to functions. Thus, these "behaviors" are mechanistic, causal descriptions of "how a system works" in terms of the interactions of structural components, flows and fundamental principles. In earlier work, we describe how we use the SBF vocabulary to provide an interdisciplinary group of undergraduate students with a common language for describing both human-designed and biological systems [12]. We found the common vocabulary provides useful conceptual anchor points for students in articulating how a system works. These anchor points are particularly useful for students trying to describe or hypothesize how unfamiliar systems function, especially those from outside of their domain of expertise.

Perhaps more importantly, for biologically inspired design, the language of SBF forces students to articulate and separate the working principles of the system from the structural details. While novice designers often focus on structure, describing behavior forces students to consider the systems interactions, the causal factors, and the underlying technical principles [5].

This framework is critical for avoiding what we call the "hairy house" problem, which we describe as follows. Assume a student wants to design a house that uses less energy to keep warm in the winter, and assume they take a polar bear as their source of inspiration. A structurally fixated, novice designer might simply transfer structure when practicing biologically inspired design; to keep a house warm, simply put fur on its outside, designing in effect, a "hairy house." The goal of biologically inspired design is to understand and transfer the causal principles, and implement those principles using materials that meet your engineering requirements. Polar bear fur insulates the bear by creating an air boundary with low thermal conductivity, so we would want students to transfer that concept to create a low-conductivity barrier using appropriate, and ideally sustainable materials (and not polar bear pelts).

The genesis of the SBF ontologies was in man-made physical design contexts, such as the early Kritik system [13]. While we have found undergraduate students to be proficient at identifying structures and functions, conceptual confusion occurs when using the term behavior with biological systems, which becomes an overloaded term. We have tried several variants on SBF, including "what-how-why," though we found that even more ambiguous and confusing in practice [6]. In applying the concept to our high school engineering course, we made the strategic decision to replace behavior with mechanism. Furthermore, since the Next Generation Science Standards (NGSS) promotes Function-Structure as a cross-cutting concept in the sciences, we felt that recognition would be higher for both teachers and students if we paired those concepts, instead of separating them, as they are in the ontology names. Thus, we present Structure-Function-Mechanism (SFM) as a conceptual cornerstone in the BIRDEE curriculum, for describing, understanding, transferring, and designing both biological and man-made systems.

The goal of BIRDEE with respect to SFM is to develop fluency in describing systems using these categories, to motivate students on the importance of understanding mechanism, and to teach students how to transfer design principles, rather than structure.

2.3 Professional Learning (PL)

The goal of the summer professional learning for the teachers in the BIRDEE project fell into four primary categories: 1) develop enthusiasm for BID 2) connect teachers to nature, 3) learn tools for BID, including SFM, that will augment the engineering design process as they know it, and 4) complete a BID engineering design project. The BID design project followed the design arc for the student curriculum, from problem definition through prototype and test, with a show and share at the end. The teachers engaged in experiential learning as both teacher and student by participating in the design project. This was facilitated by weekly points of reflection for applying their experience to how they might teach this same content. Content was delivered remotely due to COVID, with all assignments and meeting agendas published through an online education portal. Assignments included scaffolded discussion prompts, presentation slides, text documents, and photos, and a typical week included two, two-hour synchronous meetings with discussions and content presentations.

2.3.1 Structure-Function-Mechanism training

Teachers were provided with a 20-minute online training that introduced them to the concepts of SFM and why it is important for biologically inspired design and for student learning. In keeping with the problem-based inquiry method of the PL, the teachers were asked to represent biological systems prior to receiving training. Furthermore, the training was kept at a survey level, with only a few examples provided, and teachers were asked to apply SFM in their assignments. Coaching and guidance were provided as needed, either in the form of guiding questions on assignments or from feedback during team calls. Teachers were encouraged to learn from each other and to highlight positive examples from each other's presentations.

2.4 Data

The main sources of data included teachers' assignment documents and teachers' and facilitators' discussion about the assignment during the live video calls. Teachers were given a series of assignments during the 6-week professional learning (PL) and completed them over time, asynchronously. Following the timeline (see Table 1), after each assignment was completed, teachers discussed their thoughts about the assignment in a 2-hour video call. Additionally, we conducted a focus group with teachers at the end of the PL where teachers discussed their overall PL experiences.

TABLE 1: TIMELINE OF ASSIGNMENTS

Activity	Period for Activity
1.2 Found Object Investigation 1	June 8-9
1.5 Nature Walk Investigation	June 10-11
3.1 Initial Design Concept	June 22-23
3.2 Design Document	June 22-23
3.8 Low-Fidelity Prototype	June 29-30
4.0 Found Object Investigation 2	July 1-10

The complete schedule included both non-design and design activities. Table 1 shows only those design activities relevant to this analysis. We use indexes (e.g., 1.2 or 4.0) to represent the week and assignment order within that week; thus assignment 1.2 was given in week one following 1.1, while 4.0 was given in week 4. The next section includes a description of the relevant assignments and their learning objectives. We also share the responses of one teacher, Teacher 1, to provide more insight into the ways that teachers engaged with this PL.

2.4.1 Found Object Investigation (1.2, 4.0): This individual assignment required teachers to study a biological system of their choice "in the wild" and to focus on a "function of interest." Teachers were instructed to sketch the system, annotate the sketch, and describe or speculate about the how features give rise to function. They were asked to reflect over the experience, and to share and discuss their results in an online group discussion. Teachers repeated this assignment later in the course, with the additional instruction of including an SFM table and focusing on a thermal regulation function.

Example. For this activity, Teacher 1 went for walk in nature to investigate a biological system. He chose Poison Ivy, given the appealing shape. Paying attention to safety, he picked a few leaves to conduct exploration on its biological system. In this activity, he explored the external and obvious features of this poison ivy by sketching and annotating (see Figure 1). Additionally, his exploration led him to learn about some hidden features. He mentioned in his assignment, "I placed the leaves in a sandwich bag upon cutting them from the vine. I then sealed the baggy. The newer leaves are lighter green. The older leaves are darker. An hour or two after the two types of different leaves had been in separate baggies, I noticed dark spots on the bags. I was under the impression that I had rubbed against something like chocolate or ink…Then I noticed that the "ink" was on the inside of the bags. The young green leaves were excreting the dark liquid from the opening that had been created when I cut the vine. The older leaves actually seemed to have holes in the leaves. So, the fluid was excreting from the holes as well as the point where the vine had been cut."

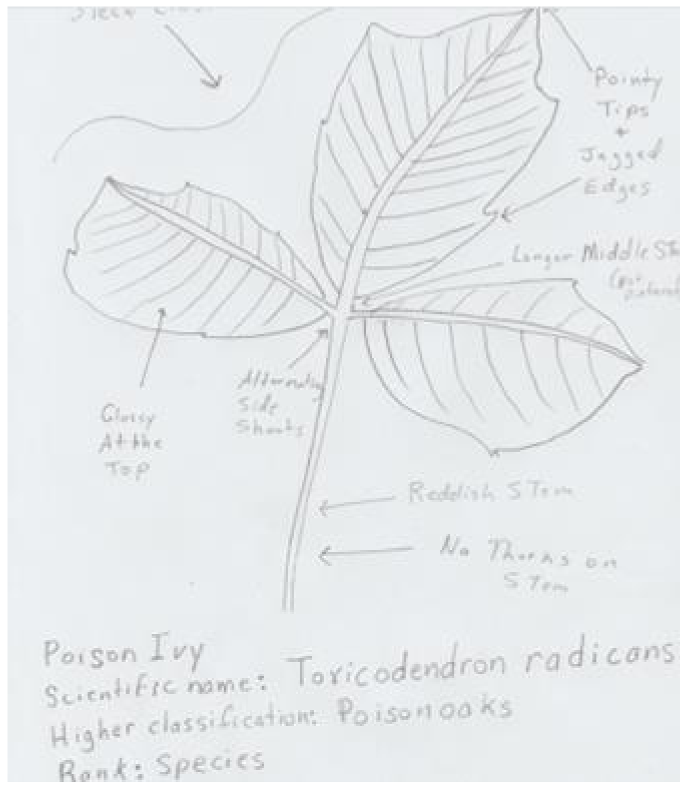


FIGURE 1: TEACHER 1 RESPONSE TO FOUND OBJECT INVESTIGATION ASSIGNMENT 1.2

2.4.2 Nature Investigation (1.5): This individual assignment asked the teachers to observe (virtually or in person) natural organisms (i.e., exotic animals and plants) as they go through their daily routines. Teachers were asked to take an engineering lens, analyze the biological and natural systems, and compare them to man-made systems. They were given prompting questions to explore the interesting functions these natural organisms perform, the structures that help them to accomplish these functions, and the ways in which they use these structures to perform these functions. Table 2 shows the sample table that was included with the assignment as a guide for their analysis.

Example. Teacher 1 was the only participant who went to a zoo to observe the animals in-person. As seen in the Figure 2, he observed the activities and behaviors of four animals and then filled out the table for all of them in his assignment. During the video call, he mentioned that while he had some difficulties understanding the functions, structures, and mechanisms, he believed he got them correct. He stated that he identified the mechanism by observing the animals, but either hypothesized the corresponding function or conducted research to identify it.

Organism	Biome	Activity	Function	Mechanism	Differences	Eng. Target
Pink Flamingo	Large alkaline or saline lakes	Head shaking	Remove expel excess mud and water	Regular side-to-side head shaking motion to remove dirt ana moisture	Humans systems use exfoliating bath sponges and/or bath clothes with soap in showers and baths to expel dirt and sweat. Towels are use to dry moisture.	An agitation system that disperses dirt and rids moisture
Lappet-Faced Vulture	Arid plains, dry Savannah, and deserts	Spread wings	Increase the surface area to receive warmth from the Sun, "Horaltic Pose"	Feathers are held rigidly upright to gain warmth from the Sun	Humans attempt to gain warmth from the Sun by laying out on beaches dressed in minimal clothing. In colder climates or conditions warm is achieved by being in doors using heating systems, wearing heavier clothing, and the use of blankets and coverers.	Heat absorption
Giant Panda	Forrest in high Altitude	Eating	Acquire food or resources for nutrition	Pandas must eat 12-28kg (up to 62 lbs.) every day to meet their energy needs.	Human systems typically eat about 3-4 lbs. of food per day as adults	Provides nutrition needed for energy and functionality
`Gamma Gamma Gorilla	Tropical Forrest	Carry young on back	Protection	Gorillas carry their "infant" young, weighing 3 to 4 pounds, on their backs to protect them during the early stages of life.	Humans may have infant children in baby buggies, car seats, or shoulder harnesses during travel to protect them.	Safe travel of young infants

FIGURE 2: TEACHER 1 RESPONSE TO NATURE WALK INVESTIGATION ASSIGNMENT.

He was able to make some comparison between the function and mechanism of these animals with similar human-made systems and suggest possible use of the mechanism observed in the animals in engineered systems. It was also observed that his descriptions used the SFM framework, as desired, though the accuracy of his classification of concepts was imperfect.

2.4.3 Initial Design Concept (3.1):

The goal of activity 3.1 was to brainstorm design ideas to solve the design challenge, which was to transport vaccine vials while maintaining an appropriate temperature range and resisting impact damage. The teachers were encouraged to think about different ideas that could be highly creative and/or highly practical, while considering the materials and fabrication constraints. The assignment asked teachers to clearly communicate and represent their ideas in any modality with which they were comfortable, including, sketches, writing, images, and graphs.

Example. Teacher 1 came up with one idea with some details and possible features. He used sketches and writing to represent his idea, which was very similar to the way he did the first Found Object assignment. He called his idea Bio-Egg. He had the system sketched, added features and structures, and described what function each feature serves and how. During the video call, he stated that the source of inspiration for his idea was the shipping of ostrich eggs. We observed less use of SFM language in his conversation around the design idea than for the found object investigation and nature investigation.

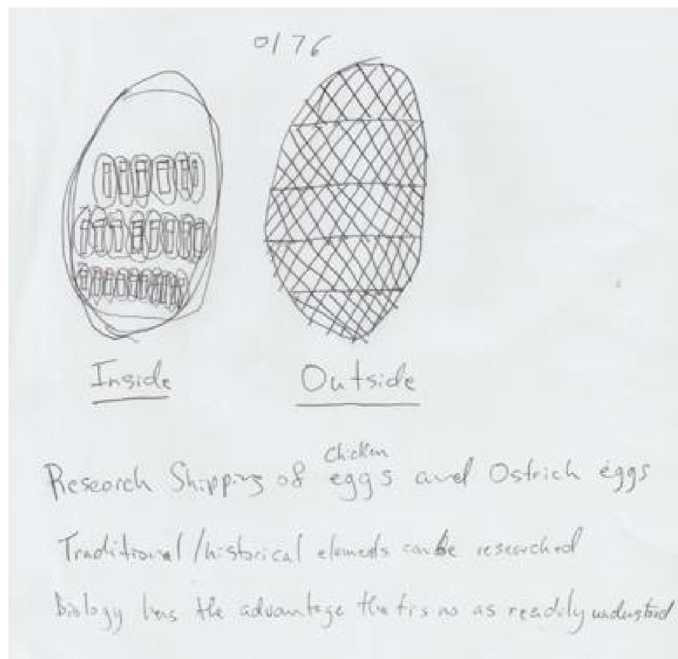


FIGURE 3: TEACHER 1 RESPONSE TO INITIAL DESIGN CONCEPT ASSIGNMENT.

2.4.4 Design Document (3.2):

Teachers were asked to identify one or more unique mechanisms used in their design idea (Initial Design Concept). At the beginning of the assignment the following elaboration on SFM was provided: "*a mechanism is: Something **[structure]** does something to something to accomplish something **[function]***." This definition was not a part of the original assignment and was included following a conversation in which the teachers struggled with the ambiguity surrounding mechanism. The definition was offered by an instructor who had used it in an undergrad context with some success. Teachers were prompted to answer these questions in a table, similar to the previous activities.

1. What function(s) does that mechanism perform?
2. What structures does the mechanism require?
3. What design problem requirement or performance objective does the mechanism meet?

Example. Teacher 1 broke down his idea to four main mechanisms aligned with four problem requirements. He then described the functions they served and the structures they needed to serve the function.

Mechanism	Function	Structures	Requirement
Egg opens from top	Access	Plastic design clicks into place	Seals liquid
Keeps cool, surrounds vaccine	Keeps vaccine cool	Gel	Maintains cool temperature
Encompases gel	Seal gel formula	Plastic bag	Keep gel sealed
Paper like material comprising egg	cushion	Paper and or shock absorbing crate	Absorb shock

FIGURE 4: TEACHER 1 RESPONSE TO DESIGN DOCUMENT CONCEPT ASSIGNMENT.

2.4.5 Low-fidelity prototype (3.8):

In this assignment, teachers were asked to create a low-fidelity prototype of at least of one of their design ideas that they proposed in previous assignments. They could use any materials they had on-hand like paper/ cardboard/ recycled material or create a virtual 3D CAD model. The assignment did not explicitly ask teachers to consider SFM. The goal was for teachers to get a sense of what their ideas would look like.

Example. As Teacher 1 was planning to create his prototype, he began by developing an SFM table. He mentioned during the call, *"I went ahead and did the SFM for the low fidelity prototype and just going over materials I use combining both of the activities."* The table was a complete version of what he had in the previous assignment. He detailed all the problem requirements he was addressing in his prototype and then included structure, function, and mechanism for them. He used this table as a map/plan for creating his prototype. Finally, he added images as he created the prototype.

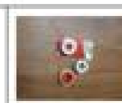
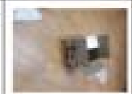
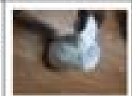
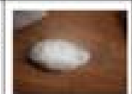
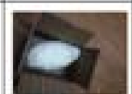
Sticky material that seals Egg	Hold Bubble wrap in place	Medical tape	Hold bubble wrap in place	
Cardboard structure for shipping purposes	Container to ship Bio-Egg	Cardboard box	House Bio-Egg for shipping	
Combines above materials to ship vaccine effectively	Save lives shipping Vaccine without damage	Bio-Egg	Ship Vaccine safely within 35 - 75 degrees Fahrenhiet, open and closing lid	
Combines above materials to ship vaccine effectively	Save lives shipping Vaccine without damage	Bio-Egg	Ship Vaccine safely within 35 - 75 degrees Fahrenhiet, open and closing lid	
Combines above materials to ship vaccine effectively	Save lives shipping Vaccine without damage	Bio-Egg	Shippable finished product	

FIGURE 5: TEACHER 1 RESPONSE TO LOW-FIDELITY PROTOTYPE CONCEPT ASSIGNMENT.

2.4.6 Focus Group (5.7)

During the focus group discussion, teachers were asked to share their thoughts and perceptions about their professional learning experience. They all agreed that learning about SFM was very interesting and something they would do in their engineering classes. One of the teachers mentioned, "*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....*" However, they mentioned that they still have confusion about SFM and struggle in understanding of SFM, "*with the SFM, I'm still struggling with that.*"

They also shared that using SFM helped them with engaging in design and believed that their students could also benefit. *"That was really really really valuable both in general, but also specifically for presenting this material and seeing where my main points were for design. And some of them were maybe informational where we all had different interpretations of SFM. Some of them just in terms of the design problem and this project and okay, I'm getting stuck on a particular part and why is that? Why do I feel stuck? And digging into that because those same sticking points are going to happen to my students."*

TABLE 2: SAMPLE CODING FROM FOUND OBJECT 1

Text	*Structure*	*Function*	*Mechanism*
I initially thought that			
the spikes on my object	spikes		
served to help transport it		transport object	
by sticking to animals		stick to animal	transport by sticking to animal [by function]

TABLE 3: SAMPLE CODING FROM INITIAL DESIGN CONCEPT

Text	*Structure*	*Function*	*Behavior*
If there is enough water in contact with our payload, this will at least slow the cooling of the payload	water, payload	slow cooling of payload	
We can also use the process of evaporation as another thermal reservoir since evaporation takes some energy	thermal reservoir		remove energy by evaporation [by principle]
If we include a mostly evacuated packet of either water or isopropyl alcohol as the external temperature rises	evacuated packet, isopropyl alcohol, water		

They stated that the found object investigation and nature investigation activities helped them explore the environment around them differently and to observe their surroundings more carefully. Teacher 1 shares about the found object activity, *"Well again for me, I just gained more specific knowledge about the things that I was tasked to look at especially as it relates to found objects, that I normally just would pass by and not really think much of it. I did get infected with poison ivy and I looked at what I could do to cure it, but I didn't really look at the specific leaf and I didn't think to ideate it and look at how the shape of the leaves were, and study it, and do experiments on it. So that's something that I was motivated to do. And the same thing with the bug that I studied that I probably would've just looked at and... because I was visiting out of state and I saw the bug and it was interesting looking."*

2.6 Method of analysis

Text analysis was performed for each assignment in which a biological or a design solution was discussed. The text included long form descriptions, presentation text, short form descriptions such as that in SFM tables, and annotations on sketches and drawings. The text was evaluated in isolation from sketches, graphics, and other visual cues. We used the protocol developed in Helms and Goel [14] for coding text, developed for the SR.BID ontology using a variation on Grounded Theory [15, 16]. Whereas in Grounded Theory a theory about a phenomenon is derived solely from data, in this variation, the theory is also derived from data, but the coding scheme is seeded with a predefined ontology. The SR.BID protocol was developed using SBF as the seed ontology, and therefore encodes for structures, mechanisms (behaviors), and functions in addition to many other elements that appear in the context of design, such as constraints, benefits, users, etc. This analysis only encoded elements of text corresponding to the concepts of interest: structure, function, and mechanism. A full treatment of the coding scheme used is provided in Helms and Goel [14].

2.7 Sample of analysis

Tables 2 and 3 show sample text from two different assignments, Found Object 1 (assignment 1.2), and Initial Design Concept (assignment 3.1). Found Object 1 is somewhat interesting because this sample was prior to introduction to SFM, and for an early sample it contains a concise explanation for how a simple structure works. In this case, the spikes (the structure), accomplishes its primary function (to transport the object), through the mechanism of sticking to an animal. A mechanism may be explained in many ways, one of the most common of which is to explain by invoking another function, or a sub-function. In this case, the mechanism is explained via the sub-function, sticking to an animal, so we annotate it [by function]. For a complete taxonomy of causal annotations, which are called "transition types" in SBF literature, see Vattam et al. [1].

The case in the Initial Design Concept provides a more direct causal account of the function by evoking a physical principle, heat loss due to evaporation. The design intends to accomplish cooling the payload (function), by surrounding the payload with water (structures), which will cool the payload by evaporation (a principle), thus the [by principle] annotation. Though we abbreviate the mechanism in our coding, the entire sentence is viewed as the mechanism.

3. RESULTS AND DISCUSSION

Tables 4-9 show the number of unique structures, functions, and mechanisms coded for each assignment, both in absolute terms and as a percentage of the total concepts for that teacher and assignment. The percent term represents the frequency of unique structure, function, or mechanism relative to the total number of unique concepts coded for that teacher for that assignment. The coding provides some useful observations.

First, we note that without a guide like SFM, teachers tended to focus on structure first and function second, especially early in the process. For example, in the first Found Object assignment without SFM scaffolding we see a high degree of structural focus

TABLE 4: NUMBER OF UNIQUE STRUCTURE CONCEPTS BY ASSIGNMENT

Structure

Teacher	FO1	Nature Walk	FO2	Initial Design	Design SFM
T1	14	16	1	10	5
T2	13	5	14	15	10
T3	15	22	7	17	7
T4	2	5	--	36	6

TABLE 5: NUMBER OF UNIQUE FUNCTION CONCEPTS BY ASSIGNMENT

Function

Teacher	FO1	Nature Walk	FO2	Initial Design	Design SFM
T1	5	18	5	9	9
T2	9	11	29	2	10
T3	3	45	4	14	3
T4	6	7	--	12	7

TABLE 6: NUMBER OF UNIQUE MECHANISM CONCEPTS BY ASSIGNMENT

Mechanism

Teacher	FO1	Nature Walk	FO2	Initial Design	Design SFM
T1	1	2	2	0	3
T2	0	2	12	0	1
T3	3	10	0	2	0
T4	1	4	--	2	8

TABLE 7: PERCENT OF UNIQUE STRUCTURE CONCEPTS BY ASSIGNMENT

Structure

Teacher	FO1	Nature Walk	FO2	Initial Design	Design SFM
T1	70%	44%	13%	53%	29%
T2	59%	28%	25%	88%	48%
T3	71%	29%	64%	52%	70%
T4	22%	31%	--	72%	29%

TABLE 8: PERCENT OF UNIQUE FUNCTION CONCEPTS BY ASSIGNMENT

Function

Teacher	FO1	Nature Walk	FO2	Initial Design	Design SFM
T1	25%	50%	63%	47%	53%
T2	41%	61%	53%	12%	48%
T3	14%	58%	36%	42%	30%
T4	67%	44%	--	24%	33%

TABLE 9: PERCENT OF UNIQUE MECHANISM CONCEPTS BY ASSIGNMENT

Mechanism

Teacher	FO1	Nature Walk	FO2	Initial Design	Design SFM
T1	5%	6%	25%	0%	18%
T2	0%	11%	22%	0%	5%
T3	14%	13%	0%	6%	0%
T4	11%	25%	--	4%	38%

with teachers 1 and 3 at 70% and 71% (Table 4). Teacher 4 is an outlier, both because the number of concepts covered were very small, half as many relative to the others and because the teacher fixated on explaining the purpose of only one, simple structure, the spikey outgrowth on a sweetgum seed. Furthermore, the sweetgum structure identified by Teacher 4 was perpetuated into all their later design concepts, suggesting early structural fixation by that teacher. When teachers did the assignment a second time for Found Object 2, which was scaffolded with a SFM table, we see that teachers 1, 2, and 3 reduced their structural fixation, and teacher 2 increased their focus on mechanistic descriptions. Teacher 4 did not complete that assignment, and teacher 1 did not cite many distinct concepts, 8 total. These results suggest that SFM scaffolding and use of the SFM table may direct teachers away from structural fixation.

Second, in circumstances where teachers focus on structure, they neglect mechanism. Without direct scaffolding in the form of an SFM table, we see that mechanism occupies 8% of concepts for the first found object and only 3% of concepts for initial design descriptions. When an engineering teacher is provided an open format to describe what they have designed, they focus on the components of the design, versus how that design works. In subsequent iterations of similar descriptions, scaffolded by SFM tables, teachers 1, 2 and 4 show increased use of mechanism in their descriptions. Teacher 3 is consistent in their approach, except for the Nature Walk, which we discuss next.

Third, the Nature Walk assignment came very early in the process and immediately following the first found object. This assignment showed an increased frequency of functional and mechanistic descriptions. For teachers 1, 2 and 3, functional frequencies increased from 25% to 50%, 41% to 61%, and 14% to 58% respectively (Table 8). Likewise use of mechanism increased from 5% to 6%, 0 to 11%, and 11% to 25% for teachers 1, 2, and 4, while teacher 3 showed a small decrease from 14% to 13% (Table 9). This assignment came immediately after SFM training, though this may not be the only cause of the change. All the found objects in the first assignment were plants: poison ivy leaf, climbing vines, maple leaf and sweetgum seed. On the other hand, the nature walk activity encouraged investigation of animals in zoo habitats. We believe watching an animal perform an active function in context, observable at human-scale, may lead to an improved understanding of the causal account of that mechanism than does trying to infer the account from a passive organism, like a plant leaf, especially if the organism is taken out of context. This suggests that active and observable, human-scale biological organisms will be better suited for training teachers and teaching students, than would static or passive systems, or systems that operate at scales that cannot be directly perceived.

Finally, we note that in the case of SFM tables, where teachers were asked to provide short descriptions of the conceptualization of how the system works into the correct conceptual bucket, the teachers demonstrated significant confusion. In two cases, teachers placed only structures in the column labeled mechanism. While teachers were able to properly identify structure and function with reasonable accuracy, in no cases were teachers able to consistently place mechanisms for their observed (biology) or desired (design) functions. They sometimes provided no mechanisms at all, as in the case where they provided structures instead. This is not to say that they did not articulate mechanisms, only that they often misclassified them. We believe this may be an artifact of the dual role of the teacher during training – that they were both designers and teachers. While focus group comments suggest they found SFM valuable for their own descriptions and designs, we believe they were in part, looking for clearly definable rules for teaching their students how to differentiate among the concepts. For example, in one exchange with the teachers, when discussing the alternative "what-how-why" approach to framing SFM, one teacher asked if there were hard and fast grammatical rules that could be used and became focused for the remainder of the conversation on identifying such rules. The teachers likewise seemed to prefer the simplified definition of mechanism included in assignment 3.2. We believe that the teachers tried simplified approaches to classifying mechanism, not because their views were simplified, but because they were experimenting with simplified rules and patterns to help teach mechanism to high school students. We find it interesting that while our data suggest that SFM training and tables increase the occurrence of mechanistic descriptions, teachers are unable to explicitly differentiate between mechanistic, functional, and structural thinking.

4. CONCLUSION

Introducing the concept of structure-function-mechanism, grounded in NGSS structure-function, provides teachers with a framework that they indicate might be useful for understanding and describing complex systems and designs. Our case study supports the standard structural bias that we see in novice designers, showing that high school engineering teachers suffer from both structural bias and fixation.

While teachers were able to grasp the structural facets of their systems, they were inclined to look for clear markers separating mechanism (behavior) and function. Because of the systems-of-systems nature of most biological systems, these boundaries were often subjective, presenting unique challenge to teachers, especially as they look for methods to teach as well as to personally understand.

Initial results from coding teachers' assignments from their professional development activities suggest that active and observable, human-scale biological subjects will be better suited for training teachers and teaching students, than would static, passive, or unobservable systems, where it is harder to extract the mechanisms due to lack of context.

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