**Proceedings of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2010
August 15-18, 2010, Montreal, Quebec, Canada**

DETC2010-28939

THE EFFECT OF FUNCTIONAL MODELING ON UNDERSTANDING COMPLEX BIOLOGICAL SYSTEMS

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ABSTRACT
Biologically inspired engineering design requires understanding of complex biological systems for use as analogues in engineering designs. In this study we seek to understand how functional representations, in particular Structure-Behavior-Function (SBF) models, enable understanding complex biological systems. Results from this study indicate that SBF representations may enable more accurate inferences about biological systems for complex and abstract questions than purely textual, or textual and diagrammatic, representations. They also suggest that no one representation is best for all types of inferences.

BACKGROUND, MOTIVATION AND GOALS
Biologically inspired (or biomimetic) design is an important and growing movement in design [1-4]. The movement is driven in part by the need for environmentally sustainable development, and partly by the recognition that nature can be a powerful source of inspiration for technological innovations. This, in turn, is driving development of educational courses and programs in biologically inspired design as well as interactive computational tools for supporting biologically inspired design in practice. The Biomimcry Guild's web portal called AskNature (http://www.asknature.org), for example, provides access to an online functionally-indexed database of research articles in biological sciences. Georgia Tech's Center for Biologically Inspired Design (http://www.cbid.gatech.edu/), as another example, offers a popular senior-level interdisciplinary course on biologically inspired design, and is planning undergraduate and graduate curriculums in the emerging interdiscipline.

Despite these and other pioneering efforts, at present there is no science of biologically inspired design, and its practice remains scattered, empirical and *ad hoc.* This *ad hoc* character of biologically inspired design, we conjecture, is in no small part due to its interdisciplinarity. This interdisciplinarity raises several fundamental questions such as: How do biologists and engineers work together in teams? What is the extent of their shared lexicon? How do engineers and biologists understand design problems? How do they communicate design ideas across disciplines? How do biologists and engineers understand biological systems? What external representations best help them develop deep understanding of biological systems?

In this paper, we focus on the last question mentioned above: what external representations, such as text, diagrams, or structured knowledge representations, best help biologists and engineers develop deep understanding of biological systems in service of biologically inspired engineering design? This question is central to development of interactive computational environments. Current interactive tools for supporting biologically inspired design provide only implicit answers to this question [5-10]. Chakrabarti et al [5] for example, describe an interactive tool called Idea-Inspire that provides a knowledge base of SAPPhIRE constructs of biological and engineered systems accompanied with text and diagrams. These constructs enable multiple Function-Behavior-Structure of a system. Nagel [8] similarly describe a tool that uses Functional Basis [11] to represent biological systems. The design of these two interactive tools implies that Function-Behavior-Structure and Functional Basis representations, respectively, help engineers understand biological systems. Sarkar & Chakrabarti [9] describe experiments with the SAPPhIRE system under different knowledge conditions. However, it is not yet clear to what degree the improvement in an engineer's design performance is a direct result of the functional representations used by the tool.

The growing number of cognitive studies of biologically inspired design too have not focused on the question of structured knowledge representations of biological systems for use in interactive tools [12, 13]. Our own earlier cognitive studies have focused on the computational processes of biologically inspired design [14], and the nature of analogies in biologically inspired design [15] such as compound analogy [16].

In a different but (in retrospect) related line of research we have been investigating the use of Structure-Behavior-Function (SBF) modeling of complex systems [17-19] to enhance understanding of aquaria ecosystems in science education. Empirical research in the SBF conceptual framework suggests that while experts understand a complex system in terms of its interrelated structure, behaviors and functions, novices express primarily its isolated structure, demonstrate minimal understanding of its functions, and largely miss its behaviors [20]. Thus, we developed interactive computational tools for learning about classroom aquaria as complex ecosystems in middle school science. Empirical research on the use of these tools in middle school classes indicates that use of SBF models as external representations leads to deeper understanding of the systems as measured by question-answering on pre- post-tests [21, 22].

The apparent success of SBF models as external representations for enhancing understanding of complex ecosystems in middle school science inspired us to examine whether these SBF models may also lead to deeper understanding of complex biological systems among college-level biologists and engineering students studying biologically inspired design. In this paper we describe a pilot cognitive study that attempts to answer the following questions: (1) Do SBF models provide any inferential capability beyond that provided by text and diagrams? (2) If so, how does the capability vary by the type of inference task, e.g. fact finding or spatial inference?

STRUCTURE-BEHAVIOR-FUNCTION (SBF) MODELS OF COMPLEX SYSTEMS

We adopt the Narayanan [23] characterization of complex systems: (1) Complex systems exhibit hierarchical structures composed of subsystems and components; (2) Subsystems and components exhibit natural behaviors or engineered functions; (3) The subsystem/component behaviors causally influence other subsystems/components; (4) The propagation of these causal influences creates chains of events in the operation of the overall system and gives rise to its overall behavior and function; and (5) These chains of events extend in temporal and spatial dimensions. A classroom aquarium, a flashlight electrical circuit, the human respiratory system, the locomotion of the basilisk lizard on water, and the movement of raindrops on the microstructures of lotus leafs are some examples of complex systems.

SBF models of complex systems originate in Chandarsekaran's [24] functional representation scheme. An SBF model of a complex system explicitly represents its structure [S] (i.e., its configuration of components and connections), its functions [F] (i.e., its intended output behaviors), and its behaviors [B] (i.e. its internal causal processes that compose the functions of the components into the functions of the system). The SBF language provides a vocabulary for expressing and organizing knowledge in an $F \rightarrow B \rightarrow F \rightarrow B \ldots \rightarrow F(S)$ hierarchy, which captures functionality and causality at multiple levels of aggregation and abstraction.

In Figure 1 we illustrate an SBF model of the self-cleaning function of the lotus leaf. The lotus leaf is interesting to engineers and others because it maintains a clean surface, despite being in otherwise dirty environments. It does this through nano-structures on the surface of the leaf that interact with water to cause it to bead up and roll off the leaf, carrying debris particles away with it.

In Figure 1, *states* of a system are represented as shaded boxes, within which are described the *components* (e.g. contaminants, water droplets) and the *properties* (e.g. location, shape, mass) and *values* (e.g. on leaf, spherical, or the variable value M) associated with those components. For each state, we include only those components, properties and values relevant to the particular state change that is occurring. The entire series of state changes along with annotations about why the states change constitute the *behavior* of the system. Connections between states are called transitions, and include a variety of explanation types that provide information about why the change occurs. One type of transition, called transition-by-function, gives rise to the hierarchical organization of SBF models as we demonstrate in the following model.

The Self-Clean *function* (Figure 1a, on the left in Figure 1) of the lotus leaf is the result of a Self-Cleaning behavior consisting of four states. In the first state, contaminants are at rest on the lotus leaf. In the second state, when a drop of water falls on the surface of the leaf, the leaf exhibits a super-hydrophobic effect, which causes the water droplet to take the shape of a sphere. Figure 1b (on the top right in Figure 1) illustrates the super-hydrophobic sub-function; note the by-function annotation on the first transition in the Self-Cleaning behavior. The arrow between the states is the *transition*, while the annotation is the *explanation*. These annotations provide causal explanations for why the state changes occur in the system. The by-function annotation includes a pointer to a function that is represented by another SBF model, albeit a very small one. In this way SBF models inherently provide function /sub-function decomposition. In the third state, after the water drop falls on the surface of the leaf, the drop rolls over the contaminants using the principle of motion of a spherical body on an inclined plane, subject to the structural constraint that the leaf is inclined and not horizontal. Figure 1c (on bottom right of Figure 1) illustrates this sub-function; again, note the by-function *explanation* of the *transition* in the Self-Cleaning Behavior serves as the pointer to this sub-function, which itself is represented with an SBF model. In the fourth state, the drop of water rolls off the leaf, carrying the contaminants with them and leaving the leaf clean.

The Cause Superhydrophobic Effect sub-function of the leaf (illustrated in Figure 1b) has is its associated behavior which is enabled by the nano-scale "bumps" structural constraint present on the surface of the leaf, by the principle of interacting surface tensions captured by Young's equation, and by the sub-function (not detailed in this model) of the nano-bumps of making the surface non-wettable. The Make Water Droplet Roll function of the leaf (illustrated in Figure 1b) too has its own causal behavior. When the water moves over the contaminants, it absorbs them subject to the constraint that the force of absorption is greater than the static forces between the contaminants and the surface of the leaf. Note that the SBF model enables access to the physical laws and mathematical equations.

The lotus leaf model presented in Figure 1 provides a representative example of an SBF model. However, this characterizes only one way of visualizing an SBF model. For the second model used in our study, we modified the representation to better express states and transitions occurring in parallel. Figure 2 shows the behavior model of the basilisk lizard, which is interesting for its ability to quickly walk on water using only its hind legs. The state of the lizard, and the state of the water over which it is walking are represented on the left and right hand sides, respectively, with a common set of causal transitions in between. In this case, the sub-functions for the by-function explanations (e.g. Leg Slap, Push Water Down and Away, Exert Lift etc.) are not further modeled. The model itself captures only the essential functions and interactions useful for explaining how the basilisk lizard walks on water.

It is important to recognize that these models are qualitative. They do not seek to provide precise, mathematical models of a system per se, but rather to capture a conceptual understanding of how a system works. Because of their flexibility, it is not uncommon to see many differences between

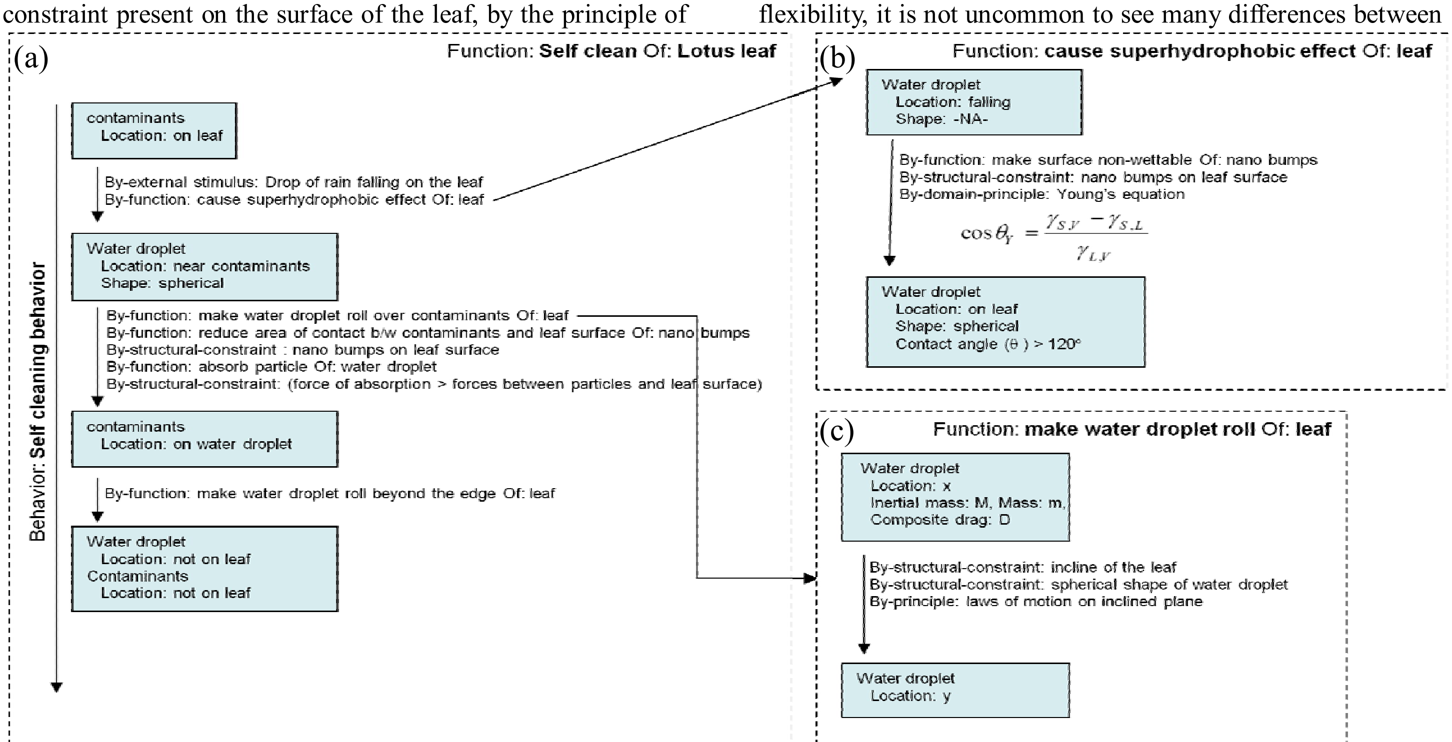

FIGURE 1: SBF MODEL OF THE SELF CLEANING FUNCTION OF LOTUS LEAF

models developed independently by two individuals.

STUDY METHOD

Study context and participants

This study was conducted as a classroom exercise for a group of 37 undergraduates enrolled in a biologically inspired design class at Georgia Institute of Technology. Of the 37 participating students, 16 self-identified as biologists and 21 as engineers. The participants were all junior and senior level undergraduates, fluent in English and familiarized with the concept of biologically inspired design through four weeks of classroom training.

This classroom exercise had both research and pedagogical goals. As a pedagogical device, the exercise served to (1) educate students on biological systems that might be useful to their design project, (2) familiarize students with differences in inferential capability afforded by different representation types, and (3) help students recognize patterns in communication and representation preferences among the different disciplines represented in the class. The pedagogical goals were realized both by participation in the exercise and by a reflective post-exercise discussion conducted after the exercise. The pedagogical goals served as additional incentive for the students to participate fully in the exercise.

One week prior to the exercise, the students received 90 minutes of classroom instruction in Structure-Behavior-Function (SBF) models. Aside from the pedagogical benefits, this ensured that students were somewhat familiar with the SBF models presented during the study, although their fluency with SBF models probably did not approach their fluency with graphs or text. Furthermore, a five minute primer was provided to the students prior to the exercise, explaining the state representation schema for SBF models used in the SBF representations.

The cover page of each packet asked students to self-report on whether their major was biology or engineering, and how familiar they were with respect to the lotus leaf, the lotus effect, the basilisk lizard itself, and the basilisk lizard's water walking ability. Students were instructed to score their familiarity on a scale from 1 to 5, where one is totally unfamiliar, and five is very familiar.

Study methodology

Students were provided one of three different modalities of detailed representations of a single biological system, and asked to answer questions about the system along four dimensions:

a) *fact finding*, the ability to find and return a single fact within the representation(s) provided.

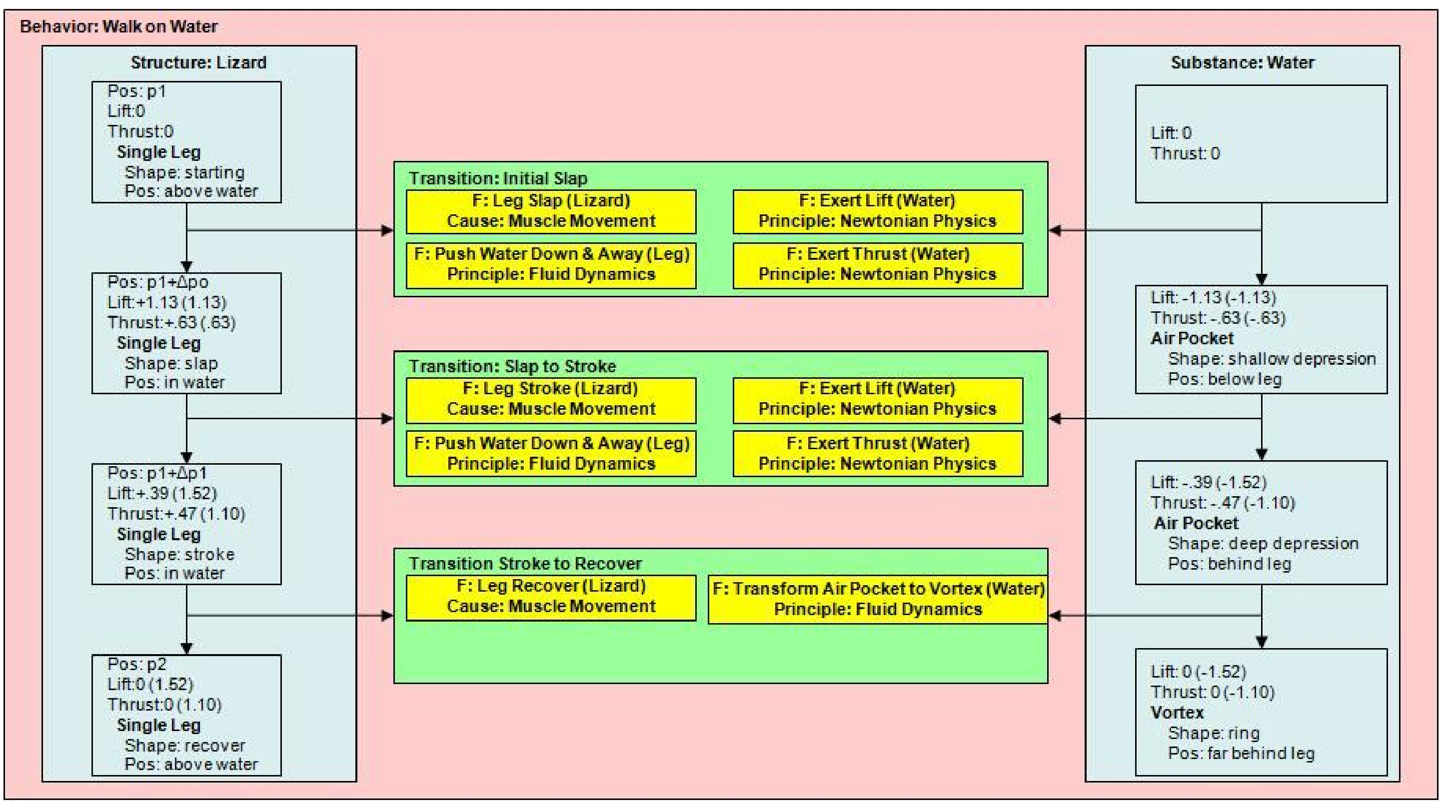

FIGURE 2: SBF BEHAVIOR MODEL OF BASILISK LIZARD WALKS ON WATER

TABLE 1: NUMBER OF SUBJECTS BY TREATMENT TYPE AND MODEL

		Lotus Leaf			
		DIA	SBF	TXT	
Lizard	DIA	-	6	3	9
	SBF	5	-	6	11
	TXT	6	7	4	17
		11	13	13	

b) *spatial inference*, the ability to reason about or recall the shape or metric relationships among components described by the representation(s).

c) *complex reasoning*, the ability to reason about casual and functional relationships among various components and interactions within the system described by the representation(s).

d) *abstract problem solving*, *the* ability to answer complex questions related to the systems behaviors, but that were not explicitly present in the representation(s).

The treatments for each model were (1) text only, (2) text plus graphical and tabular representations, and (3) text plus structured representations. The structured representation was a Structure-Behavior-Function representation, presented in diagrammatic form as shown in Figures 1 and 2. The students were given fifteen minutes to assimilate the new information and answer the questions, with a five minute period offered at the end for students who were not yet finished. The exercise was conducted twice, for two different biological systems, a lotus leaf and a basilisk lizard (lizard). These two systems were selected as representative of systems useful in the context of biologically inspired design. Each system was often cited by instructors in previous instances of the class, along with designs that were inspired by them. Table 1 shows the combinations of treatments students received for the two different models. For the basilisk lizard, seven questions were asked: two fact finding, two spatial reasoning, two complex reasoning, and one abstract problem solving question. For the lotus leaf, five questions were asked: one fact finding, one spatial, two complex, and one abstract.

Students that finished the first exercise early were instructed to close their packets, and not to look ahead to the second exercise. All students finished both exercises within the allotted time.

Exercise packets were pre-arranged such that a single student received two different modality combinations. Thus if a student had text-only modality for the Lizard, they would receive either text-plus-graphics or text-plus-structured-representation for the Lotus. This was important pedagogically so that students could reflect on differences in their own experience with the different modality combinations. This reflection was facilitated by an instructor lead discussion following the exercise. Treatment types were alternated between adjacent participants, ensuring that roughly equal numbers of treatment types were distributed. Several non-student observers and instructors seated in the classroom also participated in the exercise. The results from these observers and instructors were discarded so as not to bias results. While it was our intent to test an equal number of each modality because of the distribution to observers and instructors, and subsequent discarding of their results, some imbalance occurred.

Furthermore, during the first round of exercises, some students did not look sufficiently ahead in their packets, and were unaware that they were given more than just the text representation. When students vocalized this fact at the end of the exercise, the test facilitators asked that any students who were unaware of the second, non-text representation during the exercise record this fact on their answer sheet. All answer sheets thus noted were considered text-only in terms of the analysis. This accounts for the disproportionately large number of text-only samples during the first exercise (17 of 37, versus 13 for the second). It also explains why 4 students received text-only versions for both models, as shown in Table 1.

At the end of the exercise, prior to the general discussion, on the last page of the packet students were asked to provide feedback on their preferred representation modality. The top of the piece of the paper read as follows: “In each case you were provided with different representations (either text with SBF, text with graphs/tables, or text only.) Which representations did you prefer? Why?” Students were allowed as much time as required to answer this question.

Materials used

Text descriptions of the systems were extracted from papers describing the relevant details of their respective systems [25, 26]. The original papers were technical and difficult to read, and so were paraphrased to Flesch-Kincaid grade level score of 11.5. No mathematical formulae were present in the text descriptions.

We used SBF representations that explicitly captured the relationships between states, state properties, and the relationships between states (see Figures 1 and 2). The SBF models used were prepared earlier by the authors as sample SBF models for demonstration purposes. Graphical annotations present in these original SBF models were removed, and some formatting was altered for readability. All other content of the SBF models were preserved.

Figure 3 shows the graphical representations of the lotus leaf system including images of the systems (Figure 3a), and figures representing the operation of the system over a series of time ordered states (Figure 3b). Graphic representations were taken either directly from the corresponding academic papers, or from diagrams developed in our lab for use in augmenting SBF model descriptions, and were used without modification.

Each student was asked the same set of questions for each system. Following are a list of sample questions for both the (a) basilisk lizard system and the (b) lotus leaf system:

Fact finding:
(a) Which provides more lift, the slap phase or the stroke phase of the basilisk lizard's movement?
(b) What physical properties of the lotus leaf account for it being clean?

Spatial Inference:
(a) In which phase, slap or stroke, does the moving leg cover a greater total distance?
(b) What shape does the water droplet form on the leaf of a lotus leaf?

Complex:
(a) Which provides more thrust, the slap phase or the stroke phase of the basilisk lizard? Why?
(b) How does the water droplet move on the lotus leaf?

Abstract Inference:
(a) How could you estimate the thrust and lift generated by the basilisk lizard, without measuring anything about the lizard itself?
(b) How is this different from how water might move over a surface without the properties of the lotus leaf?

Grading method
As an informal study, answers to questions were graded by only one of the authors, a computer scientist, with neither biology nor engineering training. His knowledge of both the lotus leaf and basilisk lizard systems is derived from scientific research articles, developing SBF models of the systems, observing the biologically inspired design class, and from discussions with biology and engineering instructors in the class.

The correct answers to fact finding and spatial inference questions were unambiguous. The answers to complex questions, and abstract inference questions were subject to some interpretation, as discussed in the following section.

DATA
The self-reported familiarity scores are presented in Table 2. The self-reported mean familiarity for the basilisk lizard system was 1.74, for the lotus leaf, 2.35.

TABLE 2: SELF-REPORTED FAMILIARITY SCORE BY MODEL

Reported Score	Lotus Leaf	Basilisk Lizard
1	22	37
2	23	22
3	15	12
4	9	3
5	5	0

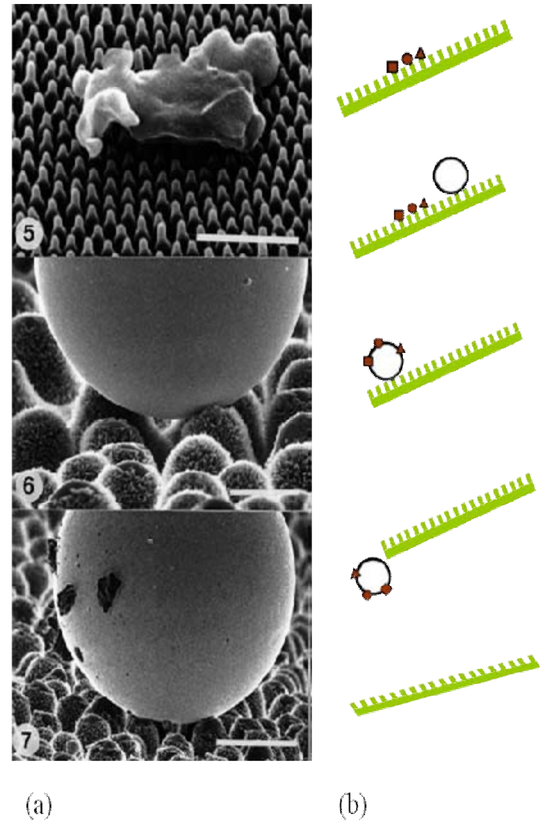

FIGURE 3: DIAGRAMATIC REPRESENTATION OF THE LOTUS LEAF

Answers to questions were categorized as either correct or incorrect. For complex and abstract questions, some unanticipated answers were received that were not initially classified as correct or incorrect, because of some ambiguity in the question language. For instance, when asking how the lotus effect is accomplished, a student might cite the underlying property accounting for the behavior (for instance hydrophobicity), or might describe the motion of the drop of water as it rolls down the leaf and pick up particles. Both are legitimate correct answers to the question. For such questions, any rational answer citing facts and following a logical thought progression were coded as correct. Where multiple correct answers were thus possible, which correct answer was provided was noted. For instance, when asked how a drop of water might proceed down a lotus leaf, the terms "rolls" "fast" "by adhesion" and "non-wetting" were all coded as rational and correct, and each given a unique identifier. For the purposes of this study, however, only the correctness of each answer was analyzed. Only obviously wrong answers were coded as wrong. For example, for the complex question "How does the water droplet move on the lotus leaf?" the answer "by spreading" was considered incorrect because it is the opposite of the correct answer (the water maintains a spherical shape and specifically does not spread.) Non-answers (blanks), accounted for 4.7% of

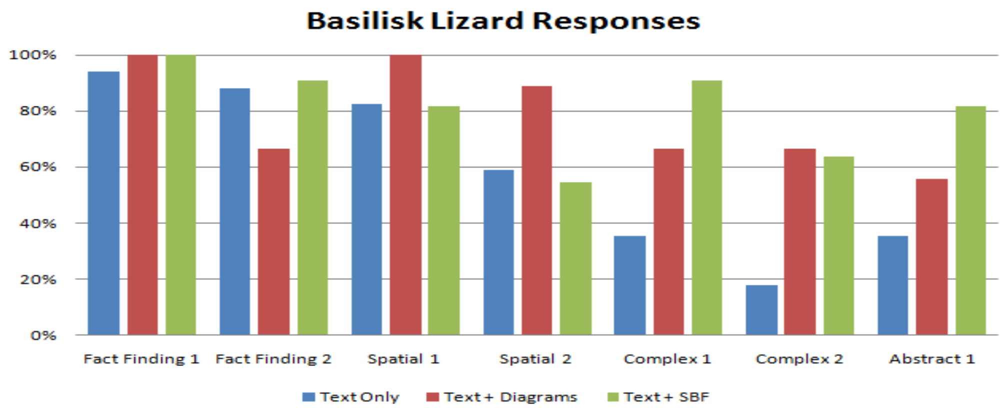

FIGURE 4: PERCENTAGE OF CORRECT RESPONSES TO BASILISK LIZARD QUESTIONS, BY TREATMENT TYPE

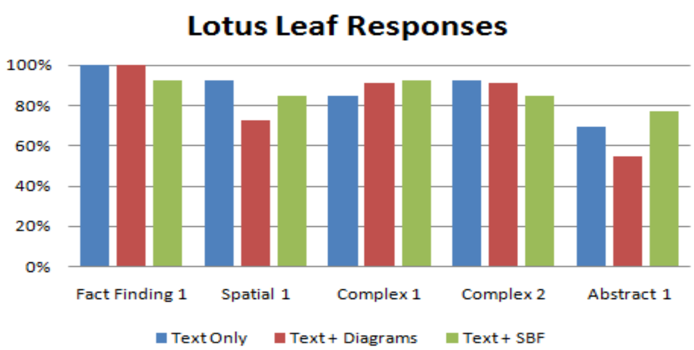

FIGURE 5: PERCENTAGE OF CORRECT RESPONSES TO LOTUS LEAF QUESTIONS BY TREATMENT TYPE

the total answers, and were provided a unique code but were considered incorrect for purposes of the analysis.

For the basilisk lizard based questions, figure 4 shows the percentage of correct answers for each question, by treatment type; figure 5 provides the same information for the lotus leaf based questions.

Table 3 reports the average percentage correct, by question, by major, irrespective of treatment.

With respect to the final question, preferred representation, interestingly some students felt strongly enough to not only comment on their preferences, but also to comment on their dislike for the SBF modality. Table 4 summarizes student preference by major, where the row heading Not SBF represents the number of students that reported a dislike for the SBF modality.

TABLE 3: PERCENTAGE OF CORRECT ANSWERS BY MAJOR

	Fact Finding 1	Fact Finding 2	Spatial 1	Spatial 2	Complex 1	Complex 2	Abstract 1
	Basilisk Lizard Questions						
Biologists	100.00%	87.50%	81.25%	56.25%	50.00%	31.25%	43.75%
Engineers	95.24%	80.95%	90.48%	71.43%	66.67%	52.38%	61.90%
	Lotus Leaf Qustions						
Biologists	100.00%		81.25%		93.75%	81.25%	43.75%
Engineers	95.24%		85.71%		85.71%	95.24%	85.71%

ANALYSIS

Familiarity Scores

Although the mean reported familiarity with lotus was greater than that for the basilisk lizard, and scores were generally higher for the lotus questions than for the basilisk lizard questions, correlation analysis between the self-reported understanding of a system and the number of correct answers show close to zero correlation (r-squared = .015 for basilisk, r-squared = .047 for lotus). Thus, self-reported prior knowledge of a system does not appear to be an important factor for this study. This is likely a result of the level of detail of the questions being asked relative to a student's perception of their own familiarity. While a student might be familiar with the basilisk lizard and the function it performs as reported through popular media, for instance, it seems unlikely that they would know or retain the particular thrust ratios discussed in an academic paper.

Question Scores

The mean score for the basilisk lizard was 4.27 out of 7 (61%), with a standard deviation of 0.87 (12.4%), while the mean score per student for the lotus leaf was a 3.7 out of 5 (74%), with a standard deviation of 0.66 (13.2%).

When assessing the significance of including SBF and diagrammatic modalities, we test the hypothesis that the proportion of questions answered with SBF or diagrams is greater or less than the proportion answered for the base rate for text only for the same question, assuming standard normal distribution. We note that for the basilisk lizard questions, the number of students n = 17 for text only, n = 11 for text plus diagrams and n = 9 for text plus SBF. Diagram plus text results are statistically different at a confidence interval of .01 for *complex 2* (z = 2.68), and are statistically significant at a confidence interval of .10 for *spatial 1* (z = 1.34), *spatial 2* (z = 1.54), and *complex 1* (1.56). SBF + Text findings are significant at the .01 level for *complex 1*(z = 2.88), *complex 2*(z = 2.68) and *abstract 1*(z = 2.41) questions. For the lotus example, no significant differences were detected for any of the questions.

Likewise tests of significance between number of correct answers for each question were run between engineers and biologists. Statistically significant differences were detected between engineers and biologists for the complex 2 question for the basilisk lizard (z = 1.34) and for the abstract 1 question for the lotus (z = 2.55).

Table 5 summarizes the results, where High indicates statistically significant difference with 99% confidence, low indicates a statistically significant difference with 90% confidence.

While not statistically significant overall, it is interesting and counterintuitive that for some questions, the additional graphical or functional information resulted in *worse* average performance. This can be seen in fact finding question 2 for the basilisk model, and for spatial question 1, and abstract question 1 for the lotus leaf model.

TABLE 5: SUMMARY OF RESULTS

	Basilisk Lizard							Lotus Leaf				
	Fact Finding 1	Fact Finding 1	Spatial 1	Spatial 2	Complex 1	Complex 2	Abstract 1	Fact Finding 1	Spatial 1	Complex 1	Complex 2	Abstract
SBF + text	--	--	--	--	High	High	High	--	--	--	--	--
Diagrams + text	--	--	Low	Low	Low	High	--	--	--	--	--	--
Major	--	--	--	--	--	Low	--	--	--	--	--	High

CONCLUSIONS

There is a growing trend to develop interactive tools for supporting biologically inspired design. Most of these tools rely on the use of functional models of biological systems. However, there is an urgent and critical need to empirically establish that functional representations of biological systems in fact facilitate deeper understanding of biological systems. In this paper we described a pilot cognitive study to determine whether functional models of one kind, namely, SBF models, enable deeper understanding of complex biological systems. We draw three preliminary conclusions from the study. Firstly, for some cases SBF representations indeed do enable more accurate inferences about biological systems for complex and abstract questions than purely textual representations. When the inference tasks require knowledge about causality, function or teleology, then, at least for understanding the locomotion of the basilisk lizard on water, the SBF representations used in the context of this study appear to provide a deeper understanding than textual or diagrammatic representations. Secondly, no one representation is best for all different types of inferences. Thus, for spatial inferences, diagrammatic representations appear to be better than SBF representations. This leads to our final conjecture: for supporting the understanding of biological systems in the context of biologically inspired design, it may be best to provide access to multiple external representations, including text, diagrams, and SBF models.

TABLE 4: REPRESENTATION PREFERENCE BY MAJOR

Preference	Biologist	Engineer
Diagram	5	18
SBF	6	1
Text	5	2
Not SBF	1	4

It is important to note that this paper describes only a pilot cognitive study that is limited in many ways. For example, the *in situ* study was conducted in a real classroom. Studies of this kind do not easily allow formal controlled experiments that isolate independent and dependent variables. Further, the study was conducted using pencil and paper. We have since built an initial version of an interactive tool called DANE (for Design by Analogy to Nature Engine) for supporting biologically inspired design. DANE provides interactive access to SBF models of complex biological systems. We have also conducted a preliminary study in our laboratory to evaluate whether DANE enhances understanding of complex biological systems. We are presently analyzing data collected from the formal study. Given the scale and complexity of the problem of understanding a biological system, it is clear that we will need to conduct many such studies before we can draw any firm conclusions.

ACKNOWLEDGMENTS

We thank the instructors of ME/ISyE/MSE/PTFe/BIOL 4803 in Fall 2007 especially Profs. Jeannette Yen and Craig Tovey. We also thank the student designers in the class for their input in this study. This paper has benefited from discussions with Spencer Rugaber, Bryan Wiltgen, and Jeannette Yen, and detailed feedback provided by the reviewers. This research was supported by an NSF CreativeIT SGER Grant (#0632519) entitled "Towards a Computational Model of Biological Analogies in Innovative Engineering Design," and an NSF CreativeIT regular grant (#0855916) entitled "MAJOR: Computational Tools for Enhancing Creativity in Biologically Inspired Engineering Design."

REFERENCES

[1] Bar-Cohen, Y. (Editor), 2006, Biomimetics: Biologically Inspired Technologies. Taylor & Francis.

[2] Benyus, J., 1997, Biomimicry: Innovation Inspired by Nature. New York: William Morrow.

[3] Bonser, R., & Vincent, J., 2006, "Technology Trajectories, Innovation, and the Growth of Biomimetics," Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, pp. 1177-1180.

[4] Yen, J., & Weissburg, M., 2007, "Perspectives on Biologically Inspired Design: Introduction to the Collected Contributions," Journal of Bioinspiration and Biomimetics.

[5] Chakrabarti, A., Sarkar, P., Leelavathamma, B., & Nataraju, B., 2005, “A Functional Representation for Aiding Biomimetic and Artificial Inspiration of New Ideas,” Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 19, pp. 113-132.
[6] Chiu, I., & Shu, L., 2007, “Biomimetic Design Through Natural Language Analysis to Facilitate Cross-domain Analysis,” Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 21, pp. 45-59.
[7] Shu, L., Stone, R., McAdams, D, Greer, J., 2007, “Integrating Function-Based and Biomimetic Design for Automatic Concept Generation,” In Proc. International Conference on Engineering Design (ICED’07), Paris, France, August 2007.
[8] Nagel, R., Midha, P, Tinsley, A, Stone, R., McAdams, D., Shu, L., 2008, “Exploring the Use of Functional Models in Biomimetic Concept Design,” ASME Journal of Mechanical Design, 130(2).
[9] Sarkar, P. & Chakrabarti, A., 2008, “The Effect of Representation of Triggers on Design Outcomes,” Artificial Intelligence for Design, Analysis and Manufacturing 22(02), pp. 101-116.
[10] Vincent, J., Bogatyreva, O., Bogatyrev, N., Bowyer, A., & Pahl, A., 2006, ”Biomimetics: Its Practice and Theory”, Journal of the Royal Society, Interface 3, pp. 471-482.
[11] Stone, R., & Wood, K., 2000, “Development of a Functional Basis for Design,” Journal of Mechanical Design, 122(4), pp. 359-370.
[12] Linsey, J.S., Wood, K.L., Markman, A.B., 2008, “Modality and Representation in Analogy,” Artificial Intelligence for Engineering, Design, and Manufacturing, 22, pp. 85-100.
[13] Mak, T.W., Shu, L.H., 2008, “Using Descriptions of Biological Phenomena for Idea Generation,” Research in Engineering Design, 19/1, pp. 21-28.
[14] Helms, M., Vattam, S., & Goel, A., 2009, “Biologically Inspired Design: Products and Processes,” Design Studies 30(5): pp. 606-622.
[15] Vattam, S., Helms, M., & Goel, A., 2009, “Nature of Creative Analogies in Biologically Inspired Innovative Design,” In Proc. Seventh ACM Conference on Creativity and Cognition, Berkeley, California, October 2009.
[16] Helms, M., Vattam, S., & Goel, A., 2008, “ Compound Analogies, or How to Make a Surfboard Disappear,” In Proc. 30th Annual Conference of the Cognitive Science Society, pp. 781-786.
[17] Goel, A. K., Rugaber, S., & Vattam, S., 2009, “Structure, Behavior & Function of Complex Systems: The SBF Modeling Language,” International Journal of AI for Engineering Design, Analysis and Manufacturing, Special Issue on Developing and Using Engineering Ontologies, 23, pp. 23-35.
[18] Goel, A., Gomez, A., Grue, N., Murdock, W., Recker, M., & Govindaraj, T., 1996, “Towards Design Learning Environments - Explaining How Devices Work,” In Proc. International Conference on Intelligent Tutoring Systems, Montreal, Canada, June 1996.
[19] Prabhakar, S., & Goel, A., 1998, “Functional Modeling for Enabling Adaptive Design of Devices for New Environments,” Artificial Intelligence in Engineering, 12, pp. 417-444.
[20] Hmelo-Silver, C., Marathe, S., Liu, L., 2007, “Fish Swim, Rocks Sit and Lungs Breathe: Expert-Novice Understanding of Complex Systems,” Journal of Learning Sciences. Routledge.
[21] Hmelo-Silver, C. E., Jordan, R., Demeter, M., Gray, S., Liu, L., Vattam, S., Rugaber, S. & Goel, A. K., 2008, “Focusing on Function: Thinking Below the Surface of Complex Natural Systems,” Science Scope, Summer 2008, pp. 27-35.
[22] Vattam, S., Goel, A., Rugaber, S., Hmelo-Silver, C., Jordan, R., Gray, S., & Sinha, S., 2010, “Understanding Complex Natural Systems by Articulating Structure-Behavior-Function Models,” To appear in Educational Technology & Society, Special Issue on Creative Design.
[23] Narayanan, N. H., 2007, “The Impact of Cognitively Based Design of Expository Multimedia,” In D. Alamargot, P. Terrier & J.M. Cellier (Eds.), Written Documents in the Workplace, Elsevier Science Publishers, pp. 243-260.
[24] Chandrasekaran, B., 1994, “Functional Representation: A Brief Historical Perspective,” Applied Artificial Intelligence, 8(2), pp. 173-197.
[25] Barthlott, W., & Neinhuis, C., 1996, “Purity of the Sacred Lotus, or Escape From Contamination in Biological Surfaces,” Planta, 202, pp. 1-8.
[26] Hsieh, S.T. & Lauder, G.V., 2004, “Running on Water: Three-dimensional Force Generation by Basilisk Lizards,” PNAS 101(48): pp. 16784-16788.