

DANE: Fostering Creativity in and through Biologically Inspired Design

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Abstract. In this paper, we present an initial attempt at systemizing knowledge of biological systems from an engineering perspective. In particular, we describe an interactive knowledge-based design environment called DANE that uses the Structure-Behavior-Function (SBF) schema for capturing the functioning of biological systems. We present preliminary results from deploying DANE in an interdisciplinary class on biologically inspired design, indicating that designers found the SBF schema useful for conceptualizing complex systems.

Keywords: Design Creativity, Computational Design, Biologically Inspired Design, Biomimetic design

1 Introduction

Biologically inspired design uses analogies to biological systems to derive innovative solutions to difficult engineering problems (Benyus 1997; Vincent and Mann 2002). The paradigm attempts to leverage the billions of biological designs already existing in nature. Since biological designs often are robust, efficient, and multifunctional, the paradigm is rapidly gaining popularity with designers who need to produce innovative and/or environmentally sustainable designs. By now there is ample evidence that biologically inspired design has led to many innovative - novel, useful, sometimes even unexpected - designs (e.g., Bar-Cohen 2006; Bonser and Vincent 2007).

Despite its many successes, the practice of biologically inspired design is largely *ad hoc*, with little systematization of either biological knowledge from a design perspective or of the design processes of analogical retrieval of biological knowledge and transfer to engineering problems. Thus, a challenge in research on design creativity is how to transform the promising paradigm of biologically inspired design into a principled methodology. This is a major challenge because biology and engineering have very different perspectives, methods and languages.

We study biologically inspired design from the perspectives of artificial intelligence and cognitive science. From our perspective, analogy is a

fundamental process of creativity and models are the basis of many analogies. Biologically inspired design is an almost ideal task for exploring and exploiting theories of modeling and model-based analogies.

We have previously conducted and documented *in situ* studies of biologically inspired design (Helms, Vattam, and Goel 2009). We have also analyzed extended projects in biologically inspired design (Vattam, Helms, and Goel 2009). In this paper we describe the development and deployment of an interactive knowledge-based design environment called DANE, which was informed by our earlier cognitive studies and that is intended to support biologically inspired design. DANE (for Design by Analogy to Nature Engine) provides access to a design case library containing Structure-Behavior-Function (SBF) models of biological and engineering systems. It also allows the designer to author SBF models of new systems and enter them into the library. We present initial results from deploying DANE in a senior-level class on biologically inspired design in which teams of engineers and biologists worked on extended design projects (Yen et al 2010). The preliminary results indicate that although we had developed DANE largely as a design library, in its current state of development, designers found DANE more useful as a tool for conceptualizing biological systems.

2 Related Work

Biologically inspired design as a design paradigm has recently attracted significant attention in research on design creativity, including conceptual analysis of biologically inspired design (e.g., Arciszewski and Cornell 2006; Lenau 2009; Lindermann and Gramann 2004), cognitive studies of biologically inspired design (e.g., Linsey, Markman and Woods 2008; Mak and Shu 2008), interactive knowledge-based design tools for supporting biologically inspired design (e.g., Chakrabarti et al. 2005, Sarkar and Chakrabarti 2008; Chiu and Shu 2007; Nagle et al. 2008), and courses on biologically inspired design (e.g., Bruck et al. 2007).

Our work on DANE shares three basic features of similar interactive design tools such as IDEA-INSPIRE (Chakrabarti et al. 2005, Sarkar and Chakrabarti 2008). Firstly, both IDEA-INSPIRE and DANE provide access to qualitative models of biological and engineering systems. Secondly, both IDEA-INSPIRE and DANE index and access the models of biological and engineering systems by their functions. Thirdly, both IDEA-INSPIRE and DANE use multimedia to present a model to the user including structured schema, text, photographs, diagrams, graphs, etc.

However, our work on DANE differs from IDEA-INSPIRE and similar tools in three fundamental characteristics. Firstly, the design and development of DANE is based on our analysis of in situ cognitive studies of biologically inspired design (Helms, Vattam, and Goel 2009; Vattam, Helms and Goel 2009). Secondly, insofar as we know, IDEA-INSPIRE has been tested only with focus groups in laboratory settings. In contrast, we have introduced DANE into a biologically inspired design classroom. This is important because from Dunbar (2001) we know that the analogy-making behavior of humans in naturalistic and laboratory settings is quite different: in general, humans make more, and more interesting, analogies in their natural environments. Thirdly, while IDEA-INSPIRE uses SAPPHERE functional models of biological and engineering systems, DANE uses Structure-Behavior-Function (SBF) modeling (Goel, Rugaber and Vattam 2009). This is important because SBF models were developed in AI research on design to support automated analogical design (e.g., Bhatta and Goel 1996, Goel and Bhatta 2004). Thus, in the long term it should be possible to add automated inferences to DANE.

An SBF model of a complex system (1) specifies the structure, functions, and behaviors (i.e., the causal processes that result in the functions) of the system, (2) uses functions as indices to organize knowledge of behaviors and structures, (3) represents behavior as a series of states and state transitions that are annotated with causal explanations, (4) organizes the knowledge in $F \rightarrow B \rightarrow F \rightarrow B \rightarrow \dots \rightarrow F(S)$ hierarchy, and (5) provides an ontology for representing structures, functions and behaviors. Other researchers have developed similar functional models e.g., Kitamura et al. 2004 and Umeda et al. 1996.

3 The Design By Analogy to Nature Engine

In the long term, DANE is intended to semi-automate analogical retrieval and transfer in biologically inspired design. Presently, DANE interactively

facilitates biologically inspired design by (1) helping designers find biological systems that might be relevant to a given engineering design problem, (2) aiding designers in understanding the functioning of biological systems so that they can extract, abstract and transfer the appropriate biological design principles to engineering design problems, and (3) enabling designers to construct and refine SBF models of biological and engineering systems.

DANE employs a client-server architecture with a centralized design repository on the server-side. Each client is a thin client whereby all data is stored, updated, and recalled from the server. This architecture supports simultaneous access by multiple users and allows users to browse or edit the most current version of the repository.

DANE is a distributed Java application running on the Glassfish application server. Data is stored in a MySQL database, and we use EJB technology to handle persistence and connection pooling. Users access the application by going to a launch website that utilizes Java Web Start to both download and execute the application as well as apply any updates that have been made since the user last launched the application.

DANE's library of SBF models of biological and engineering systems is growing. In early fall of 2009, when we introduced the system into a biologically inspired design classroom, the library contained about forty (40) SBF models, including twenty two (22) "complete" models of biological systems and subsystems. The remaining were either SBF models of engineering systems or only partial models of biological systems. Biological systems in DANE were at several levels of scale from the sub-cellular to organ function to organism.

Systems are indexed by system-function pairs and retrieved by function name (e.g., "flamingo filter-feeds self"), by subject (e.g., "flamingo"), and/or by verb (e.g., "filter-feeds"). Function names often include additional specificity with regard to the objects upon which the function acts. In this case the flamingo is feeding itself. Upon selecting a system-function pair, users are presented with a multi-modal representation of the paired system-function (e.g. the "flamingo filter-feeds self" SBF model). For example, in DANE a system can be represented in text descriptions and images, as well as through visualizations of behavior and structure models. Example text and image modalities for the "flamingo filter-feeds self" model can be seen in Figure 1.

Briefly, this model describes how a flamingo uses its tongue to create negative pressure in its slightly open mouth to draw water in, closes its mouth, and then uses its tongue to force the water out through a filter-system composed of comb-like lamellae and

mesh. The lamellae trap the food, which is then drawn into the flamingo's esophagus in the next cycle.

Behavior and structure parts of the SBF models are themselves represented as directed graphs, which may be annotated with text descriptions and images. The nodes and edges represent either structural elements and connections (for structure models) or states and transitions (for behavior models), respectively. We provide an example of a partial behavior model, this time for the system “kidney filters blood,” in Figure 2. Note that the annotations on the transitions in this figure are labeled with short-hand that denotes their type: [FN] X identifies that a transition occurs because of some sub-function X, and [STR_CON] X Y identifies that a transition occurs because of the connection between some structural component X and another structural component Y.

This “kidney filters blood” partial behavior model (a component of the larger SBF model) describes the movement of blood through the kidney through smaller and smaller vessels until the blood arrives at the nephron, where the filtration process takes place. Although in DANE the complete behavior model would be displayed, due to space constraints we only show in our figure a few states and transitions in this behavior. The sub-function “nephron purifies blood” serves as an index to yet another SBF model that describes this complex lower-level process in more detail. This provides an example of how SBF models are nested through function.

Additionally, each system is visually connected to other systems with which it shares a sub or super-function relationship. This functional hierarchy is represented as an interactive graph with nodes

representing systems and edges representing the sub/super relationships. Users may navigate between systems by double-clicking on a node. Figure 3 illustrates the functional hierarchy graph for the system “sliding filament model” and shows the browsing window with a few systems displayed, including the flamingo filter-feeding self function. The “sliding filament model” describes how muscle fibers contract, and thus the model is connected to a number of higher level animal functions (e.g. “flamingo filter-feeds self” and “basilisk lizard walks on water”), and is connected to a number of lower level molecular functions related to myosin and ATP. We can see in this one example how SBF models operate and connect functions at many scales.

By presenting complex systems in the SBF schema, which places an emphasis on the causal relationships within each system, and by making explicit the function/sub-function relationships between systems, we hypothesize that biologists and engineers will understand the systems in a way that (a) helps them identify systems that are relevant to their design problem and (b) is transferable to a design solution. For example, an engineer might scan models in DANE until he/she comes across a system that has a similar initial and objective state (a function) that matches his/her design problem. Then, by inspecting the structure and behavior of that system, the engineer might formulate a technological solution that implements a similar set of behaviors.

While SBF models can represent systems across multiple levels of scale and abstraction, and across the two domains of biology and engineering, the issue of knowledge engineering remains problematic. In

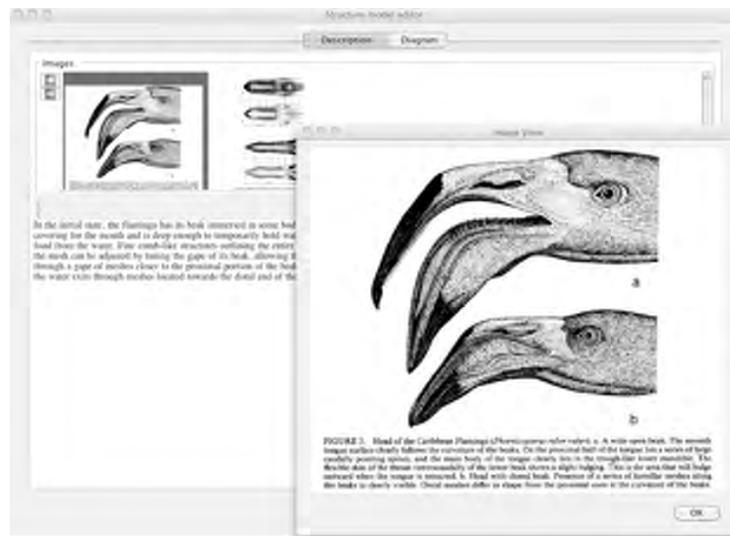


Fig. 1. Example of a multi-modal model of a flamingo's filter-feeding apparatus in DANE

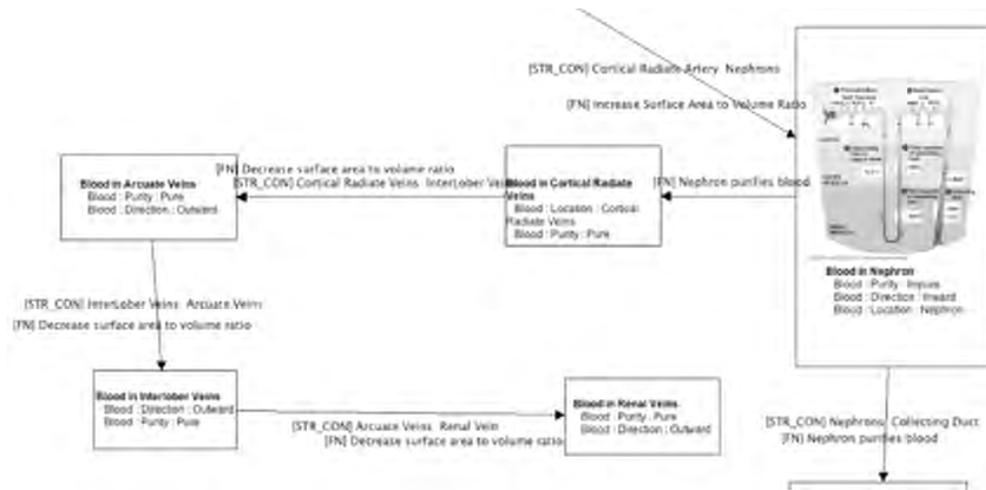


Fig. 2. Partial behavior model of “Kidney filters blood“ in DANE

particular, we found that constructing a “complete” SBF model of a complex biological system requires between forty (40) and one hundred (100) hours of work. The process of understanding the biological system (e.g. the kidney), modeling it in the SBF language, discovering faults in the model or in the modeler’s understanding, and iterating over this process consumed a large majority of the time. We estimate that just entering a complete model into DANE required somewhat less than 25% of the overall time cost.

4 Application Context

We deployed DANE in the Fall 2009 semester session of ME/ISyE/MSE/PTFe/BIOL 4803, a project-based, senior-level, undergraduate course taught by biology and engineering faculty affiliated with Georgia Tech’s Center for Biologically Inspired Design (Yen et al. 2010). The class composition too was interdisciplinary, comprising of 15 biology students, 11 mechanical engineering students, and 14 students from a variety of academic disciplines including biomedical engineering, chemical engineering, industrial engineering, material science, mathematics, and a few other engineering fields.

The course has three components: lectures, found object exercises, and a semester-long biologically inspired design team project. In the design project, teams of 4-6 students were formed so that each team would have at least one biology student and students from different schools of engineering. Each team was given a broad problem in the domain of dynamic, adaptable, sustainable housing such as heating or energy use. Teams are expected to refine the problem and then design a biologically inspired solution based on one or more biological sources to solve it. All teams presented their final designs during the end of the class and submitted a final design report.

The class is taught without any aids for design or research. Students are encouraged to perform their own research on biological systems through resources

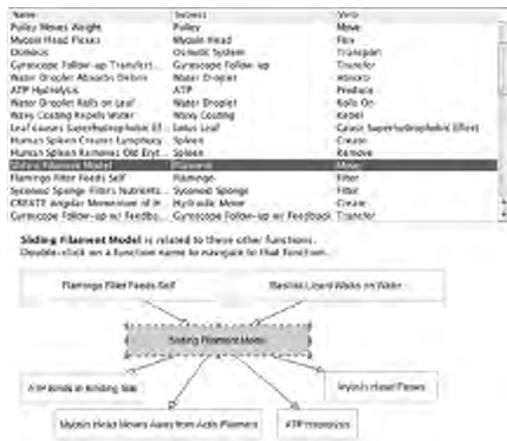


Fig. 3. List of functions and a functional hierarchy for “Sliding Filament Model” in DANE.

such as Google Scholar, Encyclopedia of Life, Web of Science, and Ask Nature. While these sources contain quality information, they typically return an overwhelming number of results, and results often are in a scientific language that is especially challenging for the non-biologists in the class to understand.

Further, students transmit information about their research to one another via PDF copies of scientific articles, meaning that all members of a team must read the raw sources. Explanations of these scientific articles within interdisciplinary teams highlight the knowledge gaps and cross-discipline communication challenges previously mentioned.

Our motivation for deploying DANE in this class was to measure its effectiveness in a classroom setting. Ideally, DANE would support biologically inspired design by exposing students to models of biological systems that would be represented in a way that is approachable by both biologists and engineers and useful to their class design projects. Although the classroom setting does not easily allow for formal controlled experiments and does not permit collection of certain types of data, it does enable observation of problem solving by real teams of people working in naturalistic settings as well as problem solving over an extended period of time. In our case, we felt that placing DANE *in situ* would provide a more accurate depiction of its usefulness, strengths, and weaknesses, as students might use it in ways that we did not anticipate and would only use it if they saw clear benefits to do so.

5 Training and Deployment

At the end of the third week of the class, our tool was introduced during class-time through an hour long tutorial session presented by the authors. Students were already comfortable with the idea of biologically inspired design, grouped in their semester design teams, and aware of their semester-long project.

The lesson began with a short discussion on the goal of DANE and an overview of SBF models. The point of this initial presentation was to motivate DANE, get students acquainted to the kind of representations that exist within the software, and provide some hands-on training with how to enter models into the system.

Once the tutorial session concluded, the students were told to direct any additional questions to an online web forum, accessible through the class portal that all students were familiar with using. We did not provide any more instructions to the students except to encourage them to use the application when they felt appropriate throughout the semester.

6 Results

The following five kinds of data were obtained during the deployment of DANE. (1) An online traffic counter recorded how many people used our application-launching web site, which gave us rough information on how often DANE was used, for students would visit the site to launch the application. (2) We kept a record of the models that were built in DANE by the students. (3) A log of the online troubleshooting forum was kept. (4) After the class, we interviewed a student from the class about her opinions and experiences with DANE. (5) The course instructors made available to us the final project reflections. In these reflections, students discussed the process by which they researched and designed their projects.

The traffic counter data (Figure 4) showed peak usages during the initial tutorial session and the days following when students received their individual credentials to use DANE and received moderate interest during the last half of the class, with slightly higher usage rates during the days around each of the three student project presentations.

We observed that 9 new models were entered into the system. All models were related to some biological system (e.g., “Baleen ram filter feeding apparatus”) or design idea (e.g., “Recycle Graywater”). Recall that a full system model in DANE contains a functional specification, a behavior model, a structure model, and textual descriptions and images for function, structure, and behavior. Of the models entered by students, all had functions, three had behavior models, two had structure models, and two had textual descriptions for their functions. None had textual descriptions for their behaviors or structures, and none had images. Qualitatively speaking, all the models entered by students were incomplete by our standards. However, as we will see in our interview, this did not necessarily

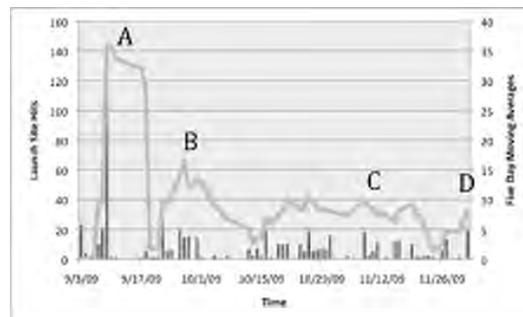


Fig. 4. Launch site traffic history. A marks the initial deployment. B, C, and D mark the project presentations.

mean the students found their own models unhelpful.

Our online troubleshooting forums contained four sub-sections: “Usability and Interface Issues” received 1 question; “Suggestions” also received 1 question; “How to Build Content” received 3 questions; and “DANE Bugs” received 2 questions. All the questions in the forum were technical in nature. No questions were about our representation schemata. The same student posted all the questions.

A 14-question interview about DANE was conducted after the semester was over with the student that posted the questions in our online forum. Although we recognize that a single student is not a sufficient sample for how the entire class felt about our tool, we felt this student in particular (due to her apparent engagement with DANE) could provide valuable feedback about the tool. The interview was taped and then transcribed with permission of the interviewee. Questions were both subjective (e.g., “Did DANE improve your understanding of biological systems?”) and objective (e.g., “Approximately how many hours, if any, did you use DANE?”).

When asked how she would rate the DANE training session from 1 to 10 with 10 being completely effective and why, the student said she would rate it a 9 because “it was reasonable that, like, everybody in the class would understand how to use DANE in that training session.”

Regarding her use of the tool, the student reported that she used it for approximately 20 hours and mainly before midterm and final class presentations because the professor gave extra credit if the team built a model on one of their 25 “inspired objects,” which were objects in nature from which they drew analogies. This answer correlates with the usage patterns. Students were encouraged before presentation dates to use DANE for extra credit, so they did, causing usage to peak during those times.

When asked how she would rate the importance of DANE to her semester-long project on a scale from 1 to 10 with 10 being of vital importance, the student gave a rating of 5, stating “it wasn't extremely, crucially vital, but it wasn't something that was not necessary” and “in the end we could've probably done without it, but I think it helped us to conceptualize.” Later in the interview when probed about what she meant by “conceptualize,” the student responded, “I mean, like, conceptualize, like, I think in boxes. Only because I'm in industrial engineering so I think in a lot of – I mean they look like flow charts. So that's what I like about DANE so I could, like...build a flow chart, essentially. From, like, the beginning stage to the end stage of a process.”

Not all responses were positive. When asked if DANE improved her understanding of biological systems, the student said no because, according to her,

“I wasn't looking up information. I was trying to input information into the database.”

Finally, when asked if she would recommend that other students use DANE, she answered yes, stating it's a “good resource” for “trying to build the analogies. And for like visualizing the connections, like the different properties. Like when my team first looked at it our overall function was regulate, and from regulate we had like regulate water, regulate energy, regulate heat, and you could just like break that up and you could go into DANE and see which- like we all independently like came up with objects in nature that had these properties and see if they were tied to each other.” In addition to analogy-making, she said that DANE would save herself and other students work if it contained a small set of systems that were relevant to the topic of the class, as this would be an easier database to browse than Google or Web of Science.

Students in the class were asked to write a final paper that reflected upon their experiences in the class. 36 such reflection papers were submitted. In six of those, DANE was mentioned by name. In two papers, both written by engineering students, the comments were explicitly positive (e.g., “I thought that DANE was a very useful tool to help decompose our system into its parts” and “A resource database (DANE!) would be VERY helpful in this class.”). In another paper, also written by an engineering student, the comments were explicitly negative (e.g., “DANE did not really help in our communication” and “it had good intentions, but I did not feel that it had great potential as an aide.”). The remaining three papers, all containing neutral statements, were written by one biologist and two engineers. More engineers than biologists mentioned DANE and only engineers had positive or negative opinions about it. Three of the six reflections mentioned DANE as a research repository, two described it as a modeling tool, and one described it in terms of aiding communication.

7 Challenges

Based on the observed results of our deployment, we have drawn several lessons. The first is overcoming the cost/benefit hurdle of systems requiring intensive knowledge engineering. Students were not willing to invest the time and effort to build models because they saw no personal benefit. Likewise, without a sufficient number of models, students found the system of little use as a reference resource. However, at 40 – 100 hours per model, building a library of sufficient breadth for general usability is a significant challenge.

The primary value to students of DANE was the use of SBF schema to (a) organize their understanding of systems, and (b) test their own ability to represent a design case. In our student interview, the student mentions that DANE was a useful tool for conceptualizing systems and in making analogies. Additionally, she said that the repository would improve her research process if enhanced with models that were relevant to the topic of the class. We had developed DANE mostly as a library of SBF models of biological systems, and the potential use of SBF schema as a conceptualization tool was mostly implicit in our thinking. We incorrectly assumed students would build and share models, which would incrementally enhance the value of the tool.

Although DANE only explicitly appeared in one-sixth of the final reflections, the perspectives provided are illuminating. We can clearly see that some students view it as a repository, some as a modeling/design environment, and at least one as a communication medium. These reflections act as evidence that, four months after the application's deployment, some students were still aware of DANE and thinking about it in terms that align with how we hoped they would think about it.

However, our other observations suggest that students were unconvinced of DANE's usefulness in whatever role they perceived it filling. Over half of the days the application was deployed received less than 10 hits; we had only one user engaged in our support forums; and our traffic peaks nearly always occurred during times when those peaks could be explained either by novelty (the peak right after the initial deployment/credential handout) or by an offer of extra credit (the peaks near the presentation times).

Another lesson comes from the quality of the student-built SBF models in DANE. The student models are incomplete, often specifying the functional parts but lacking the important associated behavior and structure models. Although the student we interviewed described our training session as effective, the model sparseness might suggest that students did not understand the training session. Alternatively, the models could be the result of students being uninterested in DANE and doing only the minimal amount of work required to get their extra credit, which returns us to the issue of motivation. The models could also be a symptom of students' not knowing their biological systems well enough to articulate them in a model.

8 Conclusions

In this paper, we described an interactive knowledge-based design environment - DANE - that provides access to a small library of SBF models of biological and engineering systems. We also described the deployment of DANE to help interdisciplinary design teams performing biologically inspired design in an extended design project in a classroom setting.

While our goal was to test our initial hypothesis that DANE would serve as an aid to assist biologists and engineers in (a) identifying useful solutions, and (b) in transferring solutions to a design solution, student engagement with the technology was too low in the classroom context to provide sufficient test data. Although we struggled with properly motivating DANE's usage and with gathering enough data to determine exactly how and why students were using it, we succeeded in the sense that the students were able to use DANE when they wanted and both the student we interviewed and two of the final project reflection journals said that DANE was a useful addition to their workflow.

Note that the results of our experiments with DANE are nowhere as neat or clean as those described by Sarkar and Chakrabarti (2008) in their work on IDEA-INSPIRE. We believe this difference is primarily because Sarkar and Chakrabarti report on controlled experiments with individual designers working on selected problems for short durations in laboratory settings. In contrast, we deployed DANE in a large design class, the designers worked in teams, the teams selected their own problems, the problem solving unfolded over a semester, and we had access to only a small portion of the design teams' work. It is for this same reason that we could not measure the efficacy of DANE for design ideation using quantitative measures such as frequency, novelty, variety, and quality (e.g., Shah, Smith and Vargas-Hernandez 2003).

On the other hand, the *in situ* deployment of DANE in a naturalistic setting led us to the result about DANE's utility as a conceptualization tool. Although we had developed DANE largely as a library of SBF models of biological systems that designers may access to address their engineering problems, we found that at this stage of its development, designers found DANE more useful as a tool for conceptualizing a complex system, with the SBF scheme enabling the designers to organize their knowledge of complex systems. We conjecture the utility of DANE as a design library may grow with the size of the library.

The lessons we learned emphasize the need for application deployment to be an iterative process and for early *in situ* deployment with target users. Had we developed DANE in isolation and only tested it in controlled situations, the problem of motivation and the insight into the importance of DANE as a conceptualization tool (as opposed to primarily as a repository) would have been difficult, if not impossible, to realize. More broadly, DANE suggests one way in which knowledge-based theories of functional modeling of complex systems may be used to support design creativity in and through biologically inspired design.

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