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Running Head: Understanding Complex Systems

Comparing expert and novice understanding of a complex system from the perspective of  
structures, behaviors, and functions

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## Abstract

Complex systems are pervasive in the world around us. Making sense of a complex system should require that a person construct a network of concepts and principles about some domain that represents key (often dynamic) phenomena and their interrelationships. This raises the question of how expert understanding of complex systems differs from novice understanding. In this study we examined individuals' representations of an aquatic system from the perspective of structural (elements of a system), behavioral (mechanisms), and functional aspects of a system. Structure-Behavior-Function (SBF) theory was used as a framework for analysis. The study included participants from middle school children to preservice teachers to aquarium experts. Individual interviews were conducted to elicit participants' mental models of aquaria. Their verbal responses and pictorial representations were analyzed using an SBF-based coding scheme. The results indicated that representations ranged from focusing on structures with minimal understanding of behaviors and functions to representations that included behaviors and functions. Novices' representations focused on perceptually available, static components of the system, whereas experts integrated structural, functional, and behavioral elements. This study suggests that the SBF framework can be one useful formalism for understanding complex systems.

Comparing expert and novice understanding of a complex system from the perspective of structures, behaviors, and functions

As our world becomes progressively interconnected, there is a growing need to focus on the dynamic nature and multi-level organization of phenomena. As such, complex systems are pervasive in many aspects of the world around us, exemplified in phenomena that range from human respiration to fish tanks to the braking system of a car. Making sense of a complex system is a difficult task because it requires one to think abstractly and often challenges current beliefs regarding phenomena. There are several alternative ways of making sense of such systems, what Collins and Ferguson (1993) have termed “epistemic forms.” For example, one might look at complex systems from the perspective of a system dynamics model, aggregate behavior, or structure-behavior function (SBF) analysis.<sup>1</sup> SBF seems to be a particularly promising mode of analysis for this domain because it focuses on causal understandings of the relationships among different aspects of the system. This is consistent with a great deal of research on expertise that has demonstrated that experts organized their knowledge around deep principles of a domain (Chi, 1981; Larkin, 1980; Norman, Trott, Brooks, & Smith, 1994; Wineburg, 1991). This has been demonstrated in domains such as physics, medicine, and history. This paper extends the research on expertise to complex systems by presenting a preliminary study that examined how children, naïve adults, and experts represent their knowledge of an aquarium system.

The characteristics of complex systems make them particularly difficult to understand. They are comprised of multiple levels of organization that often depend on local interactions (Ferrari & Chi, 1998; Wilensky & Resnick, 1999). The relationships across these levels are not intuitively

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<sup>1</sup> Collins and Ferguson (1993) refer to this as form and function analysis.

obvious. For example, in learning about ecological systems, one needs to envision how genes, individuals, populations, and species interrelate. An ecosystem can be viewed from the level of the individual organism to the level of the environment as a whole (Wilensky & Resnick, 1999). In human biology, phenomena occur at the anatomical, biochemical, and physiological levels. For example, respiration occurs at a cellular level as well as at the organ system level. The levels are interdependent with each other. When cells need oxygen, not only does the lung move more deeply than usual but the heart may beat faster to get more oxygen to the tissues. In an ecosystem, the animals provide carbon dioxide needed by the plants for photosynthesis and the plants provide oxygen needed by fish to utilize energy. A disturbance at one level or component of the system can easily affect others.

Studies of complex systems demonstrate that understanding focuses on the perceptually available structures (Gellert, 1962; Hmelo, Holton, & Kolodner, 2000; Mintzes, Trowbridge, Arnaudin, & Wandersee, 1991; Wood-Robinson, 1995). Invisible, dynamic phenomena pose considerable barriers to understanding (Feltovich, Coulsen, Spiro, & Dawson-Saunders, 1992). One reason for this is that processing all the simultaneous events and interactions pose a substantial load on working memory because of the mental simulation process and rule-based inferences needed to construct a complete mental model (Graesser, 1999; Narayanan & Hegarty, 1998). Moreover, making connections among different levels of a complex system places added demands on working memory. This is particularly true because many systems are characterized by complex causality; in other words, there may be many intermediate steps that intervene between cause and effect, which may not be linear (Perkins & Grotzer, 2000). Finally, complex systems may also have emergent properties that may not be fully predictable from the behavior of individual components (Wilensky & Resnick, 1999).

A review by Perkins and Grotzer (2000) found that students tended towards very simple causal explanations of complex phenomena. When students reasoned about effects, they missed the connectedness within the system and the complex causal relationships. One reason for this is that learners tended to focus on the structure of systems rather than on the underlying function. In another study, Chi, DeLeeuw, Chiu, and Lavancher (1994) asked students to read a passage about the circulatory system. They found that most of the functional aspects of the system were implicit and difficult for students to infer. Only students who engaged in a large amount of self-explanations were able to make those inferences.

Thinking about emergent phenomena involves the recognition that a system can have multiple causal factors and these occur at both a micro level and macro level. In two teaching experiments, Penner (2001) examined students' understanding of complex systems as they simulated building a termite nest. Students walked around the room dropping pieces of paper (corresponding to the materials in termite nests) according to a small set of simple rules and then made observations about the aggregate patterns that resulted. Students had difficulty in connecting phenomena occurring at the microlevel with those that occurred at the macrolevel. A second study used a model of cellular automata (a self contained universe with a small set of simple rules) to elicit learners' ways of thinking about emergence (Penner, 2000). Participants were asked to think about how patterns occur, and how changes in one level of the system can affect other levels. Participants based their understanding on their existing knowledge and construed phenomena as resulting from a direct consequence of a single cause. As they explored the cellular automata, participants became aware of the distinction between the different system levels (macro versus micro), the static (but not dynamic) properties, and were able to recognize some of the interactions within levels though they continued to ascribe central causation to the macro level.

Complex systems often involve concepts that can be in conflict with learners' prior experience. Resnick and Wilensky (1998) found that most people have what they referred to as a "centralized mindset," preferring explanations that assume central control and single causality. This is consistent with expert-novice comparisons of complex systems thinking (Jacobson, 2001). Jacobson interviewed undergraduate students and complex systems experts and found that students favored simple causality, central control, and predictability. Expert explanations demonstrated decentralized thinking, multiple causes, and the use of stochastic and equilibration processes.

Making sense of complex systems requires that a person construct a network of concepts and principles about some domain that represents key phenomena and the interrelationships among different levels of the system, whether it is macro to micro or structure to function. Despite the emergent nature of complex systems, there are deep principles that explain behavior in such systems and account for the relationships across levels. Research has demonstrated that people can transfer deep principles of complex systems across domains when examined in the context of simulations (Goldstone & Sakamoto, in press). Thus, an important research question is how do some of these deep principles map onto people's existing understanding and can they provide springboards for future learning? The findings concerning learners' intuitive focus on the perceptually available and observable patterns and simple causal explanations suggest that Structure-Behavior-Function (SBF) theory may provide a deep principle that is useful for thinking about complex systems. SBF theory accounts for a complex system's multiple interrelated levels, and its dynamic nature. This framework has been used for explaining and justifying design of physical devices such as electrical circuits and heat exchangers (Goel et al., 1996; Weld, 1983).

The SBF framework allows effective reasoning about the functional and causal roles played by structural elements in a system by describing a system's subcomponents, their purpose in the

system, and the mechanisms that enable their functions. Goel et al (1996) used SBF theory to model reasoning about a cooling device. More specifically, structures refer to elements of a system (e.g., fish, plants, and a filter are some of the elements that comprise an aquarium). Behaviors refer to how the structures of a system achieve their purpose. These are the interactions or mechanisms that yield a product, reaction, or outcome (e.g., filters remove waste by trapping large particles, absorbing chemicals, and converting ammonia into harmless chemicals). Finally, functions refer to why an element exists within a given system, that is, the purpose of an element in a system (e.g., the filter removes byproducts from the aquarium). We define function contextually.<sup>2</sup> The distinction between behavior and function can be confusing because of contextual issues. For example, from the perspective of an aquarium system, fish respiration is a behavior that releases waste products. If we were analyzing the fish as a system, we might consider respiration as a function and gas exchange and various cellular reactions as the behavior. Weld (1983) offered a similar analysis concerning the explanations of physical devices such as a car engine.

In earlier research, Hmelo et al. (2000) showed that the SBF principle was a useful framework for examining how children understand the respiratory system. They accomplished this in the context of having middle school students design artificial lungs. The design activities, with an implicit emphasis on function, helped the students construct an improved understanding of the function of the respiratory system and think more about behavioral mechanisms, but their understanding of the behaviors was as likely to be incorrect as correct. This occurred because the conceptual tools (the structure-behavior-function models) were not made explicit and there was no mechanism for the students to test their models and obtain dynamic feedback. In this paper, we

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<sup>2</sup> Weld (1983) makes a distinction between function and role. Role is function in context. We do not make that distinction here and refer to contextualized function.

extend this work to an aquarium ecosystem as we examine how well the SBF framework serves as an epistemic form that captures the differences between expert and novice understanding.

## Method

### *Participants*

The participants were 11 seventh grade students from a public suburban middle school, 11 pre-service teachers from a large public university, and eight experts. The experts were individuals who have been involved in aquatic systems either professionally or recreationally for 10 to 30 years. The former group (“the biologists”) included established academic researchers who held an advanced degree in biology. The latter expert group (“the hobbyists”) consisted of individuals who had maintained numerous aquaria for more than 10 years and were active members of a local aquarium society. The preservice teachers received course credit for participating in the study, and the experts were paid for their participation. Only one participant in each of the middle school student and preservice teacher groups reported having an aquarium at home, and three from each group reported that they had studied about aquaria.

### *Procedure*

We conducted individual interviews that ranged from 20 to 40 min. All interviews were tape-recorded and transcribed. Initially, the interviewer presented participants with a piece of paper that had a three-sided rectangular shape (representing an aquarium), along with color markers. The participants were asked to draw a picture of “anything you think is in an aquarium” while thinking out loud. If needed, the interviewer asked the participants for further clarifications as to his/her drawings. Once participants completed their drawing, the interviewer began asking questions.

The interviews included open-ended questions and problem solving activities designed to elicit participants' knowledge about aquarium systems. Some questions asked about a system's structure (e.g., what is in a fish tank?), others elicited knowledge of the functioning of structures in a system (e.g., what do fish do in an aquarium?), and others inquired about the behavioral mechanisms of structures in an aquarium (e.g. what happens when a filter breaks?). The participants were also given a list of items and asked how these related to an aquarium (e.g., air stone, heater, gravel, etc.). In addition, several what-if problems were posed. In these problems, participants were asked what would happen if the system was perturbed. For example, one question asked "what do you think would happen if you decide to add 10 new fish to the 12 guppies already existing in a twenty gallon tank?"

#### *Coding and analysis*

Participants' transcribed interviews were coded according to an SBF coding scheme for the presence or absence of a target concept. The coding scheme identified a target list of aquarium structures and a list of corresponding behaviors and functions. The researchers coded each interview for evidence of the presence of SBF concepts. For example, any mention of plants ("I am drawing some fake plants") or gravel ("there is the sand on the bottom") was regarded as evidence of a participant's representation of plants and/or gravel as a structure. Similarly, a mention of a fish hiding ("fish come by and they hide in there between the little plants") or bacterial processes ("bacteria...changes the ammonia into nitrate and then nitrate into nitrate back into clean water") was coded as a behavioral concept. This was coded as a behavior because it refers to a mechanism for how the cleaning of water (a function) was accomplished. An utterance that mentioned filter removing byproducts (" a filter filters out the organic waste") or light as an energy source for plants and algae ("live plants, some other organisms need the light to help photosynthesis") was coded as a

functional concept. One primary researcher conducted the majority of the coding and a second independent research assistant coded 20% of the transcripts. Inter-rater agreement conducted on 20% of the interviews was 96.5% for structures, 92.5% for behaviors, and 93% for functions. Additional qualitative analyses were conducted to capture the richness and depth of participants' representations that transcended the more formal coding.

## Results

### *Quantitative analyses*

As expected, experts identified more concepts across the SBF framework than the novice groups (see Table 1). A 2 x 3 mixed ANOVA was conducted to examine the differences between experts and the two groups of novices in their representation of structures, behaviors, and function. There was a significant interaction between the level of expertise and SBF concepts ( $F(4, 52)=14.30, p<.001$ ). There was no difference among the groups for the numbers of structures mentioned ( $F(2, 27)=2.78, p>.05$ ) but there were differences for behaviors and functions ( $F(2, 27)=24.58$  and  $24.19$ , respectively;  $p's<.001$ ). Post-hoc Student-Newman-Keuls tests indicated that the experts knew more about both functions and behaviors than the middle school students or the preservice teachers ( $p<.05$ ), and that the preservice teachers did not differ from the middle school children. These results indicate that experts have more functional and behavioral understanding of this complex system whereas novices, regardless of age, have a more structural representation.

### *Qualitative analyses*

An examination of the transcripts indicated additional qualitative differences between experts' and novices' understanding. Experts provided more elaborate responses as well as demonstrating a more integrated understanding that cut across the SBF levels. The experts

consistently used at least two of the three SBF framework elements in their responses. This was primarily evident in the descriptions of their drawings. All experts mentioned not only the various structures that can be found in an aquarium, but also discussed the structure's behaviors and/or functions. For example, in a description of his aquarium drawing, one expert said:

...there is usually some kind of substrate, either gravel, sand.. and sometimes you have rocks and um with certain kinds of fish it's necessary to have rocks, uh because they like to breed in the rocks....and other times the rocks are just decorative....

In this example the expert mentions a few structures (gravel, rock) but continues to discuss the function of the rocks in the aquarium when he mentions that the fish breed in the rocks and that the rocks have a decorative purpose in the aquarium. The former can be coded as a function of a fish (fish reproduce) and the latter can be coded as a function of a rock (decoration). A novice participant responded to the same instructions with the following:

I will draw pebbles on the bottom like rocks and stuff ...I know there are rocks and stuff and then there are plants usually that grow...

This participant mentioned numerous structures but did not offer additional behavioral or functional information even when probed. This response was limited to structures present in his/her representation of an aquarium. Integrated expert responses were also evident in the latter part of the interview where participants were presented with problems. For example, in a response to a question regarding the difference between a river and a lake fish, one of the experts noted:

The ones in the river that are swimming in strong currents will have to be very strong swimmers. The one in the lake will have to get its food probably in small areas. They probably have a small ecosystem where they swim in...some of them have camouflage, ahh

some they are very fast swimmers, some of them have armor on their backs, some of the catfish like they have like armor plating on their backs. So all the fish won't bother them.

Once again, the expert includes numerous structural and functional differences in his response.

Most novice participants indicated primarily a single structural difference between the two fish that were related to the fish's ability to swim in each environment:

Fish in a river probably uh probably bigger and stronger because they have to fight against currents sometimes and fish in like a lake is pretty still so they can be like pretty much anything like small fish, big fish.

Another interesting pattern appeared within our expert group. Upon careful reading of the interviews, we noticed some differences between the biologists and hobbyists. The biologists focused on the abstract biological processes and mechanics of the fish tank as a system whereas the hobbyists focused on concrete aspects relating to maintaining the health of the fish. Both groups had rich representations but they had different emphases. For example, in a discussion on how fish food is related to aquarium systems, the biologists provided a more abstract, scientific explanation of the importance of digestible animal protein and vitamins in a fish's balanced diet.

... it has to be balanced food containing carbohydrates, fats and proteins and for the younger ones you wanna more proteins, and for most fish, around 40% protein is very good diet...

So that what we call fish meal is a meal that is produced from fish and bone meal, is a meal that is produced from bone, and these things go as constituents into fish feed, and so they provide a nice balanced protein. But in addition you must make sure there is sufficient vitamins in the fish feed.

The hobbyists provided information about feeding schedule, popular food brands, and other food products.

There's Aquarian or Tetramin or some of the other color flake foods that are very good for a basic diet. Never over feed them, just feed a little bit and just let them look hungry...you can get specialized foods for a specific fish. Um, Hikari makes a nice line of foods for guppies, cichlids, um carnivorous fish. There are pellets you can get that sink or float, uh you can buy frozen food, frozen brine shrimp is a wonderful basic food for fish, but you can also get frozen blood worms, uh Daphnia, all sorts of stuff. Then if your parents, or your spouses, are willing, you can buy live foods for your fish.

Like the biologist, the hobbyist is making references to the need for high protein when she talks about live foods and the carnivorous cichlids. However, the hobbyist description is very concrete and situated in specific fish that need a high protein diet, particular brands of food ("Hikari, Aquarian, Tetramin") and the discussion of live foods.

Furthermore, it appears that the biologists were better able to capture the global, dynamic interdependencies within the system. The hobbyist provided more focused, local explanations concerning the relationships between and among structures and their associated functions and behaviors. For example, in a response to questions concerning the function of a filter in an aquarium, the biologists focused on the properties of a filter as a substrate for bacterial growth and proceeded to explain the role of bacteria in an aquatic system. Some continued to describe the relationship between the filtration mechanism and such processes as pH balance in the system (see Figure 1). The hobbyists indicated that the function of a filter is to remove various wastes or byproducts from the aquarium and circulate the water in the aquarium (see Figure 2). As in the food example, the hobbyists understand the relation between waste and pH but they discuss it situated in the context of how the filter keeps the tank clean.

## Discussion

The results of this study clearly indicate that structures are the most cognitively available level of a complex system for novices. In particular, those structures that are most perceptually salient are best represented. For the experts, the behavioral and functional levels serve as the deep principles that organize their knowledge of the system. Understanding the behaviors and functions of a system indicate a more elaborate network of concepts and principles representing key phenomena and their interrelationships. It was not surprising to see that the experts mentioned functional elements more than behavioral and structural concepts, as multiple behaviors and structures may combine to perform various functions. Moreover, functional aspects of the system deal with end results but behavioral mechanisms deal with dynamic and often invisible processes that are difficult to represent.

Our qualitative analysis demonstrated the fine differences in the mental representations of different sorts of experts. We did not consider that an expert's purpose in learning about aquaria would affect his or her mental representation. Biologists think in global ecosystems terms whereas hobbyists think in more local terms of what it takes to maintain healthy (and happy, as was noted by several hobbyists) fish. The hobbyists' understanding is more situated in concrete aspects of the aquarium. These differences were not expected and are worth further investigation to illuminate the relationship between one's goals and the nature of the representation constructed.

In this study we introduced a framework that accounts for the different levels of a complex system. Breaking down complex systems into structural, behavioral and functional levels may aid learners in the process of making the implicit functions and behaviors of a system explicit, and may provide a schema that can be used to understand a number of complex systems. The SBF framework appears to be a deep principle that maps onto expert ways of knowing about complex

systems. Further work needs to be done to ascertain how general this principle is. Hmelo et al. (2000) demonstrated that for the respiratory system at least, the SBF principles, implicit in learning through design activities, have some promise for helping students learn about complex systems. Our program of research is actively engaged in investigating other systems and exploring how to capitalize on the SBF framework as an example of an epistemic form to support learning about complex systems.

The SBF framework offers a way for learners to look behind the scenes at phenomena that are not readily perceptually available. Complex systems are an important part of the world that we live in and, as such, are recognized as a key idea in national science standards (National Research Council, 1996). Organizing learning around deep principles such as SBF might enable students to understand new complex systems they encounter (Collins & Ferguson, 1993). That, of course, is an empirical question and part of the work that will follow up this brief report.

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Table 1

Means and standard deviation for total number of structures, behaviors, and functions by expertise group.

Group	N	Structures	Behaviors	Functions
Middle School	11	12.27 (1.35)	6.64 (2.98)	8.73 (3.69)
Pre-Service Teachers	11	11.91 (1.14)	8.18 (2.09)	8.45 (3.17)
Experts	8	13.13 (0.64)	15.13 (2.95)	19.00 (4.11)

Figures

1. Biologist mental model
2. Hobbyist mental model



