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Learning Functional and Causal Abstractions of Classroom Aquaria

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Abstract

Structure-Behavior-Function (SBF) models of complex systems use functions as abstractions to organize knowledge of structural components and causal processes in a system. We describe an interactive learning environment called ACT (Aquarium Construction Toolkit) for constructing simple SBF models of classroom aquaria, and report on a case study on the use of SBF thinking and the ACT tool in middle school science classes. We present initial data indicating that SBF thinking supported in part by the ACT tool leads to enhanced understanding of functions and behaviors of aquaria.

Keywords: Science education, Middle school science, Complex systems, Ecological systems, Functional models, Interactive learning.

Motivation and Goals

Understanding of complex systems enables important tasks such as monitoring, measurement, sensemaking, troubleshooting, explanation, prediction, diagnosis, redesign and design. Thus, understanding complex systems has been recognized as a key idea in science education in national science standards (National Research Council, 1996) as well as local standards (e.g., New Jersey Department of Education, 2006).

However, understanding complex systems is cognitively hard not only because of the large number of components and variables in a given system, but also because complex systems are dynamical and contain feedback loops (Forrester 1968) and exhibit hierarchical structure but are only nearly decomposable (Simon 1996); causal processes at one abstraction level in a complex system emerge out of interactions among components and processes at lower levels; and while some components of a complex system may be visible, many components, relations and processes typically are invisible. Thus, understanding complex systems challenges cognitive resources such as attention, memory and perception. The juxtaposition of understanding complex systems as an educational standard and the cognitive difficulty of understanding complex systems in turn poses a practical challenge for cognitive and learning sciences.

Theories of understanding complex systems in terms of functional models use functions as abstractions for organizing knowledge of structural components and causal processes (e.g., Chandrasekaran 1994a, 1994b; Kitamura et al. 2004; Rasmussen 1986). In Structure-Behavior-Function (SBF) models, for example, Structure refers to components of a complex system as well as connections among the components; Behaviors pertain to causal processes in the complex system; and Functions are abstractions of structural components and causal behaviors (Goel et al, 1996; Prabhakar & Goel, 1998; Goel, Rugaber & Vattam 2009). Representations of structural components and causal processes specify the functions they accomplish; representations of functions in turn act as indices into the components and processes that combine to accomplish them.

The SBF theory of understanding complex systems has led to lesson plans and interactive tools for learning about complex systems in science education. Our ongoing ACT project, for example, is an interactive learning environment that enables middle school children to construct and simulate SBF models of classroom aquaria (Vattam et al. 2010). An initial study indicates that teacher-led SBF thinking about aquaria, supported in part by use of ACT by small teams of students, led to significant improvement in understanding the basic structure, behaviors and functions of aquaria. However, we also found that in practice, middle school teachers and students did not use ACT the way we had planned. Instead of using ACT to construct and simulate full SBF models of aquaria, middle school students in our studies used the tool mainly to construct SBF graphical models of aquaria (Jordan et al. 2009).

In this paper, we report on a new study that utilizes a new version of the ACT interactive tool. The new version of ACT (ACT3) directly builds on our observations of SBF thinking practices in middle school science classrooms in the initial studies as well as feedback from the middle school teachers and students on the use of the previous version of ACT (ACT2). Preliminary results from new studies of SBF thinking about aquaria, stimulated, scaffolded and supported in part by the new ACT tool, appear to replicate the findings from the earlier studies with the new and more engaging tool.

The SBF Theory of Understanding of Complex Systems

Narayanan (2007) characterizes complex systems as follows: complex systems exhibit hierarchical structures composed of subsystems and components; subsystems and components exhibit natural behaviors or engineered functions; the subsystem/component behaviors causally influence other subsystems/components; 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 these chains of events extend in temporal and spatial dimensions. The origin of both Narayanan's characterization and our SBF models lies in Chandrasekaran's (1994a) Functional Representation (FR) scheme. Chandrasekaran (1994b) traces the development of FR; Goel, Rubager, Vattam (2009) describe the evolution of SBF from FR. Briefly, (1) the structure portion of an SBF model of a complex system specifies the "what" of the system, namely, the components of the system as well as the connections among them. (2) Behaviors specify the "how" of the complex system, namely, the causal processes occurring in the system. A behavior typically comprises of multiple states and transitions among them. The transitions are annotated by causal explanations for them. (3) Functions specify understanding of the "why" of the system. A function is a teleological interpretation of the components and processes in the system. (4) A component of a complex system can itself comprise a system and thus have its own SBF model. (5) The behavior of a system specifies the composition of the functional abstractions of its subsystems into the system functions.

Other researchers have described similar functional models of complex systems, e.g., Rasmussen (1986) and Kitamura et al. (2004). Although the various functional models differ in many features, they typically share some key characteristics, viz., explicit representation of function, use of functional representations to organize knowledge of causal behaviors and structural components, a hierarchical system-subsystem organization of knowledge, a view of causal behavior as an intermediate abstraction between structure and function, and domain-independent vocabularies for representing structure, behaviors and functions of complex systems. Erden et al. (2008) provide a recent survey of functional models of complex systems and their use in design.

Note that in the SBF theory of understanding complex systems, functions are mental abstractions, and thus are not intrinsic to the complex system. In case of designed systems, a functional abstraction corresponds to an intended output or observable behavior of a system, subsystem, or component. However, since functions are abstractions, we have also used the SBF theory to model natural systems including biological systems such as the human heart and ecological systems such as aquaria. Like designed systems, natural systems exhibit the types of causal processes and multiple levels of abstraction that characterize complex systems. We use function as a lens through which to view complex biological systems as well. For example, we may model a pond as being able to regulate the chemicals inside its water to maintain a livable environment for fish and plants. We may also specify the invisible causal process that achieves this self-regulation of the pond. In addition, we may state how this causal process combines functional abstractions of other processes and subsystems into the self-regulation function of the pond. In this functional representation of the pond, functional abstractions provide explanations for the relevance of specific subsystems in the context of a causal process.

Since SBF models explicitly represent functions, they differ fundamentally from causal models of complex systems (e.g., Chi 2005). The interactive tool called Betty's Brain (Biswas et al. 2005) is a good representative of the use of causal models in interactive learning because it too works in the same general domain (ecology) and targets the same general audience (middle school students). The innovation in the system lies in transforming the role of students into teachers of problem-solving software agents (Betty). This role transformation is motivational and engaging to middle school students. The models that students help Betty build, however, are causal graphs, with no mention of function and only implicit specification of structure. Although SBF models also represent behaviors in the form of causal graphs, the behavioral representations are grounded in the structure and indexed by their functional abstractions.

ACT: Interactive Construction of SBF Models

Empirical studies in the SBF framework show that while aquaria experts and hobbyists typically understand aquaria in terms of their structure, behavior and function, novices such as middle school students and pre-service teachers familiar with aquaria focus on the visible structure, show minimal understanding of function, and show little evidence of understanding the invisible causal behaviors (e.g., Hmelo-Silver, Marathe & Liu 2007). Thus, we developed a suite of interactive tools called RepTools that included SBF-inspired function-centered hypermedia (Liu & Hmelo-Silver 2009) as well as NetLogo simulations of aquaria generated by experts (Hmelo-Silver et al. 2007). Using the SBF coding scheme to analyze students' work on pre- and post- tests and the metrics for measuring SBF understanding of complex systems developed earlier (Hmelo, Holton & Kolodner 2000), we showed that the use of RepTools leads to deeper SBF understanding of complex systems in middle school science classrooms.

Although RepTools provided a useful learning environment, it did not provide a knowledge construction facility that allowed students to explicitly articulate their SBF understanding of complex systems. However, we know that scientists *construct* models of complex systems they seek to understand (Clement 2008; Nersessian 2008). From a constructivist perspective, much of learning entails active, social construction of knowledge (Palincsar 1998), and research on interactive learning increasingly emphasizes collaborative construction of external representations (Kozma 2000; Lajoie et al. 2001; Suthers 2006).

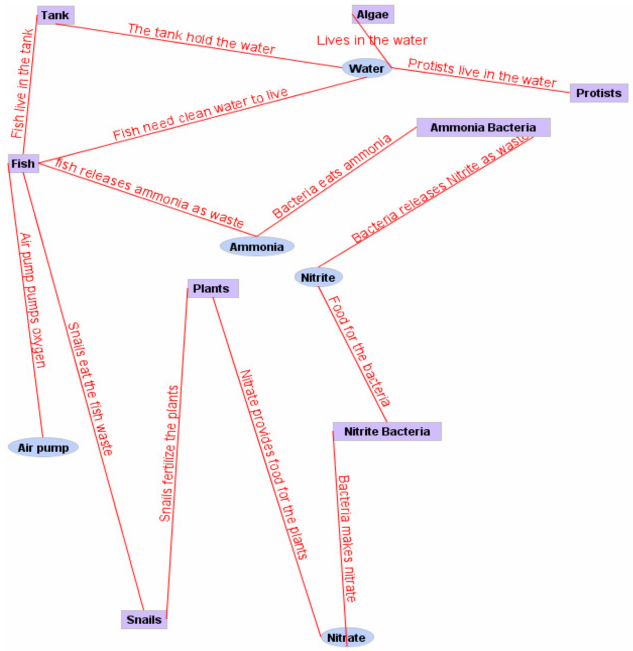


Figure 1: Model Graph of the nitrification process designed by a 7th grade student using ACT3.

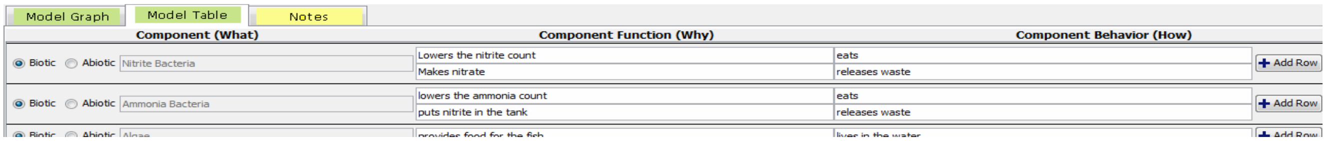
Thus, we developed an interactive learning environment called ACT that provided a tool (called SBFAuthor) for constructing SBF models of classroom aquaria in middle school science (Vattam et al. 2010). In order to adapt the SBF modeling language to serve as an effective modeling tool for learners, we augmented it with a visual syntax to obtain vSBF: a visual SBF modeling language. Creating an SBF model of a particular complex system in vSBF now becomes an exercise in drawing an annotated, flowchart-like diagram of the system using the modeling primitives provided by the language. ACT also integrated SBFAuthor with the Netlogo simulation platform (Wilensky 1999; Wilensky & Resnick 1999). In addition, ACT provided access to extant RepTools. The goal was to encourage middle school students to understand complex systems in terms of functional abstractions and casual behaviors. The intended method was teacher-led SBF thinking supported by the use of ACT for construction, simulation and revision of SBF models of classroom aquaria.

In an initial study conducted in 2008, we introduced the original ACT tool (ACT2) into three middle school classrooms consisting of one hundred and fifty seven students (Jordan et al. 2009). One example of SBF thinking used by the three middle school teachers in the initial study pertained to the nitrification process. The nitrification process is the process by which an aquarium cleans itself of waste that is poisonous to fish. Fish release ammonia in their waste, a highly poisonous chemical; nitrosomonas consume this ammonia and output nitrite, while nitrobacters eat this nitrite and release nitrate. Nitrate, though still poisonous to fish in large quantities, is much less dangerous than ammonia. In this example, the structural components in the system are the fish and bacteria. These components serve certain functions; for example, one function of the nitrosomonas is to clean the water of harmful ammonia and provide food for nitrobacters. Of course, this function is merely our teleological interpretation of this action of nitrosomonas, since (insofar as we know) the bacteria do not intentionally set out to serve a purpose to the fish. The behavior by which these nitrosomonas accomplish cleaning is through a natural ingestion/output behavior. In this example, it is also possible to see how SBF models may examine systems at multiple levels of abstraction. One could state that the aquarium as a whole serves the function of cleaning itself, and the behavior by which it accomplishes this is the nitrification process. One can also imagine how a similar analysis could be applied to *how* bacteria eats one chemical and outputs another.

Our initial study indicated that teacher-led SBF thinking, supported in part by use of the ACT tool, led to statistically significant improvement in understanding of classroom aquaria as a complex system (Vattam et al. 2010). The finding appeared robust in that it was independent of the teaching styles of the three middle school teachers in the initial study. We also found the middle school students in our initial study did not use the ACT tool as we had intended. Instead of using ACT to construct and simulate SBF models of the nitrification process described above, middle school students in our studies used the tool mainly to construct simple SBF graphical models of the process (Jordan et al 2009). This may have been in part because the 1-week and 2-week science units in which the ACT tool was used were too short for students to become familiar enough with SBF thinking as well as the ACT tool to construct and simulate SBF models of the nitrification process. It may also partially be due to difficulty in understanding the notions of states and transitions between states. Detailed feedback from some middle school teachers suggested the need for SBF tables that list the structural components, causal behaviors, and their functional abstractions.

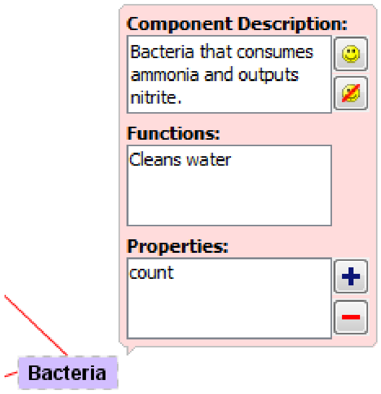
The New ACT: Simplification of SBF Models

Given our observations of the practice of SBF thinking and learning in the initial study, as well as the feedback from middle school teachers and students in the study, we redesigned the ACT interactive environment. The new ACT environment (ACT3) supports two tools: SBFAuthor and RepTools. Further, SBFAuthor enables the construction of simple, partial, single-level SBF models through a Model Graph tool and Model Table tool that work in conjunction with each other. These can be seen in Figures 1 and 2.



Component (What)	Component Function (Why)	Component Behavior (How)
● Biotic ○ Abiotic Nitrite Bacteria	Lowers the nitrite count Makes nitrate	eats releases waste
● Biotic ○ Abiotic Ammonia Bacteria	lowers the ammonia count puts nitrite in the tank	eats releases waste
● Biotic ○ Abiotic Algae	provides food for the fish	lives in the water

Figure 2: The Model Table derived from the previously shown Model Graph.



Component Description:
Bacteria that consumes ammonia and outputs nitrite.

Functions:
Cleans water

Properties:
count

Bacteria

Figure 3: Dialog for adding details to the structure in the model graph. Note the specification of the function of the component.

Model Graph: The Model Graph enables users to create the structural portion of an SBF model in terms of its structures (components and substances) and their associated connections; Figure 1 depicts a Model Graph actually constructed by a student in the classroom. The structure model is presented as a graph. For each component or substance in the structure, a corresponding node is created. Nodes are linked together by behaviors, which are represented by lines drawn between nodes. Functions of the structures and behaviors are added using a dialog window (see Figure 3), as well as the Model Table (see Figure 2). In this way, students can define and connect structures, behaviors and functions in an externalized view, which helps guide them toward a more expert-like understanding. Most importantly, this allows students to explicitly define the functions of the system in order to better understand how larger processes emerge from underlying functions.

Model Table: The Model Table is an organizational tool intended to allow students to engage in their natural thought process when first encountering a complex system. An example can be seen in Figure 2. The Model Table features three columns: one for Structure, one for Behavior, and one for Function. Structures are linked to Behaviors in a one-to-many association, while Behaviors are linked to Functions in a one-to-one association. The Model Table is more than a preliminary brainstorming tool, however. Adding structures to the Model Table will automatically result in their creation on the Model Graph. Behaviors and Functions appear in the Model Graph after their addition to the Model Table, through the Structure's pop-up dialog menu. The control works both ways: new Structures, Behaviors and Functions added on the Model Graph automatically appear on the Model Table.

RepTools: ACT also links to the extant RepTools. RepTools was designed to accompany a physical aquarium installed in each classroom. It provides digital tools that feature function-centered hypermedia from which students can read about the structures, behaviors, and functions occurring within an aquarium system (Liu & Hmelo-Silver 2009). It also includes a micro and macro-level NetLogo-based simulations (Wilensky 1999) developed by experts. The macro-level simulation enables students to test ideas about fish spawning and water quality, and the micro-level simulates the nitrification process that occurs within an aquarium as part of its biological filtration (Hmelo-Silver et al. 2007). In combination, these digital tools allow students to not only test ideas about the aquarium system but also gain insight into the explanations behind the processes and outcomes that occur at multiple levels within the aquarium.

Methods

Setting

Overall, two hundred and seventy three (273) students participated in this 2009 study from four middle schools classrooms in central New Jersey - three from seventh grade and one from the eighth grade. Their science teachers integrated this unit as a part of their regular science instruction. Prior to beginning the study, none of the students were taught to use SBF as a representational tool for complex systems. All four teachers attended an evening workshop where they were introduced to these digital tools prior to implementation in the classroom. The curriculum unit lasted from one to two weeks.

Besides the eighth grade classroom, none of the other classes had a physical model of the aquatic ecosystem (aquarium) as a part of their classroom environment. In order to prepare for the unit, the researchers set up aquariums in the remaining three seventh grade classrooms. Students used the digital tools (ACT, SBFAuthor, RepTools) on laptops while working in small groups, which varied from 2 to 6 students per computer, to generate models for analysis in this study.

Classroom Instruction

The four science teachers appropriated the curriculum and implemented it based on their individual scientific knowledge and learning styles of their students. While all the teachers used the SBF as a representational tool to organize their thinking about complex systems, there were variations within actual implementations of the curriculum.

SBF Introduction: Two teachers decided to begin the instruction with a discussion on the aquarium and focus on SBF as an initial activity using the ACT Model Table. The other teachers adopted the reverse strategy. Their introduction to the unit began with description of the SBF while illustrating it from students' immediate environment (for e.g. the classroom as a complex system). This top down effect was intended for the students to think about the SBF from a micro to macro level.

Modeling Aquatic Ecosystem: While some teachers emphasized the importance of the models as a means to represent ideas in summative fashion, other teachers chose to use the modeling task throughout implementation as a means to continually formulate and refine ideas. Additionally, some teachers chose to have students model the entire system, while other teachers had students generate a model based on a portion of the system that corresponded quite closely to one of the NetLogo simulations.

Figure 1 illustrates a model graph created in ACT by a 7th grade student as part of an SBF model construction activity in one of the middle school classrooms. This figure shows the one of the systems frequently modeled in the classrooms: the nitrification process, described previously. Structures are shown as nodes (purple for biotic structures, blue for abiotic structures), while behaviors link together structures that directly and relevantly influence one another. Although not depicted in the figure, inside the structure boxes are statements about a component's function as indicated in the dialog box of Figure 3; these functions can also be seen in the Model Table in Figure 2. In this way again, students are encouraged to recognize and explicitly state the functions of the system, reinforcing a functional understanding.

Results

To assess the effectiveness of the SBF-driven curriculum and technology, identical tests were administered before and after engagement in the aquarium unit. These tests asked about the structures, behaviors and functions of the aquaria, and were also given problems to solve regarding aquarium processes. To examine learning with respect to SBF, we coded the pre- and post- tests using an SBF coding scheme (Hmelo, Holton & Kolodner 2000). Structural components, such as fish, plants, filter, was coded as structure. A reference to the mechanisms of how the components worked was coded as behavior. For example, a behavior of the plants could be absorb some of the carbon dioxide in the fish tank and produce oxygen through photosynthesis. Reference to the outcome of a behavior was coded as function. For example, a function of the filter could be to clean and circulate water. All tests were coded blind to condition by one rater.

Table 1: Pre- Posttest Results

	Structure	Behavior	Function
Pretest Mean (SD)	8.08 (2.624)	3.80 (2.107)	4.78 (2.924)
Posttest Mean (SD)	9.33 (2.347)	6.20 (2.766)	8.12 (3.241)
t(273)	5.60*	11.65*	12.55*
Effect size	0.24	0.44	0.47

**All p<.05*

In this preliminary study, the objective was to ensure that the SBF curriculum described here is successfully increasing understanding of functions and behaviors. Since students already are generally familiar with the structure of aquaria, increases in understanding of structure are considered a baseline for comparison of how the curriculum enhances understanding of functions and behaviors. Table 1 shows initial results from the pre- and post- tests collapsed across the four middle school classrooms consisting of 273 students. The first number in the first two rows refers to the Mean and the second number in parentheses to the Standard Deviation. As indicated by the effect sizes, gains in structural understanding were modest, while we saw the greatest effect size for increase in behavioral (or causal) and functional understanding for all groups. These tests suggest that the SBF-driven curriculum and the ACT technology effectively increase understanding in terms of the deeper concepts of functions and behaviors. Thus, these results replicate the findings from our initial study. A sibling paper (Honwad et al. 2010) that too appears in these proceedings focuses on the use of RepTools in the ACT learning environment and reports on more recent data collected in 2010.

Conclusions & Open Issues

Functional models use functions as abstractions to organize knowledge of complex systems. We are pursuing a research program that investigates the use of Structure-Behavior-Function modeling for helping middle school children understand complex systems such as classroom aquaria (Hmelo-Silver et al. 2008; Jordan et al. 2009, Vattam et al. 2010). In this paper we described a new version of an interactive tool called ACT that enables middle school children to author simple SBF models of complex processes such as the nitrification process that results in self-cleansing in aquaria. We also described teacher-led SBF thinking in multiple classrooms supported in part by use of the ACT tool by small teams of middle school children. Preliminary results from the SBF-driven science curriculum in this study indicate significant improvement in understanding of the basic structure, behaviors and functions of aquaria. These results appear to confirm initial results from earlier studies.

Of course, there remain many open issues, including the following three. Firstly, now that we have experimentally affirmed that the SBF curriculum and ACT technology is effective in learning about functions and behaviors of aquaria, there is a need to conduct controlled experiments. In particular, there is a need for finer analysis of the effectiveness of SBF thinking and the ACT tool based experiments featuring many conditions, such as curriculum without software and software without curriculum. Secondly, there is a need to determine whether the improved understanding of the functions and behaviors of aquaria is enabling improved reasoning about tasks such as establishment and maintenance of aquaria. Thirdly, there is growing evidence that middle school teachers on their own are appropriating SBF meta-models and transferring them to other complex systems such as the human digestive system (Hmelo-Silver et al. 2010). There is a need to determine if middle school children too are appropriating and transferring SBF meta-models to other complex systems.

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