Abstract Title Page

Title: Systems and Cycles: Learning about Aquatic Ecosystems

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Abstract Body

Background:

Being able to analyze complex ecosystems is fundamental for becoming ecologically-literate citizens (Jordan, Singer, Vaughan, & Berkowitz, 2009; Sabelli, 2006). Like all complex systems, making sense of ecosystems is challenging because they transcend spatial, temporal, and cognitive boundaries (Pickett, et al, 1997) and necessitate understanding how different components, mechanisms and phenomena are interconnected (Covitt, Gunckel, & Anderson, 2009; Jacobson & Wilensky, 2006; Jordan et al., 2009; Mohan, Chen, & Anderson, 2009). Furthermore, complex systems are comprised of multiple interrelated levels that are dynamically related, making it difficult even for experts to understand and to predict (Hmelo-Silver & Azevedo, 2006; Jacobson & Wilensky, 2006; Simon, 1996).

A range of studies have demonstrated that it is particularly challenging for learners to grasp relationships within systems (Ben-Zvi Assaraf & Orion, 2005; Gallegos et al 1994; Penner, 2000). Often, learners focus on simple linear relationships and visible components of an ecosystem (Hmelo-Silver, Marathe, & Liu, 2007; Hogan, 2000; Hogan & Fisherkeller, 1996; Leach et al. 1996; Reiner & Eilam, 2001). In clinical interviews, when novices were asked to identify features of an aquarium system, they tended to emphasize visible components, such as fish and rocks, and rarely mentioned invisible components, such as oxygen, nitrogen, and bacteria (Hmelo-Silver, Marathe, & Liu 2007; Hmelo-Silver & Pfeffer, 2004). Other research has found that student explanations favor single causal and linear connections between system components (Grotzer & Basca, 2003).

A promising approach for promoting systems thinking in a way that can enable students to think about multiple interacting components and their fates is encouraging Structure-Behavior-Function (SBF) thinking (Goel et al. 1996; Hmelo-Silver et al. 2007; Goel, Rugaber & Vattam, 2009). Artificial Intelligence (AI) theories of model-based analogies in engineering design have led to both the methodology and technology for building models of physical systems through Structure-Behavior-Function (SBF) modeling (Bhatta & Goel 1997; Chandrasekaran, Goel & Iwasaki 1993; Goel 1991, 1996; Goel & Batta, 2004; Goel & Chandrasekaran 1989). An SBF model of a system explicitly represents its structure [S] (i.e., its configuration of components and connections), its functions [F] (i.e., its output), and its behaviors [B] (i.e. its internal causal processes that enable the functions of the components into the functions of the system).

Empirical research has demonstrated that experts represent complex systems in terms of interrelated structures, behaviors and functions, whereas novice understanding is characterized primarily by identifying isolated structures, demonstrating minimal understanding of functions, and largely missing system behaviors (e.g., Hmelo-Silver, Marathe, & Liu, 2007; Hmelo-Silver & Pfeffer 2004). Based on this research, we hypothesize that using SBF to guide conceptual representations provides a deep principle that should help students understand multiple complex systems (Hmelo-Silver et al., 2007; Goldstone & Sakamoto, 2003).

Here we describe a study for which we enacted a two-week aquarium unit. The technology consisted of a suite of computer tools: a function-oriented hypermedia (Liu & Hmelo-Silver, 2009), simulations of macro- and micro-level processes (Liu & Hmelo-Silver, 2008; Gray et al. 2008), and the Ecosystem Modeling Toolkit (EMT, building on earlier work with the Aquarium Construction Toolkit; Vattam et al., 2011).

Purpose / Objective / Research Question / Focus of Study:

In this research, we present both the design and preliminary testing of a technology-intensive classroom intervention designed to support middle schools students' understanding of an aquatic ecosystem. The goals of our intervention are to help learners develop deep understanding of ecosystems and to use tools that make the relationships between a system's structures, behaviors, and functions explicit.

Setting:

The research reported here comes from data in three public middle schools in suburban school districts in the Northeastern United States. Four teachers used the instructional intervention was conducted during regular science classes.

Participants:

All students who returned consents in the three schools were included in the study. A total of 311 students completed both the pre and post test.

Intervention / Program / Practice:

An important goal of our instructional design is to provide learners with opportunities to engage with ecosystems phenomena, particularly those that are not available to their unaided perception. Learners find many ecosystem phenomena hard to understand because they have not had experiences thinking about those processes that are dynamic and outside their perceptual range (Jacobson & Wilensky, 2006). The SBF conceptual representation also provides a scaffold for overall knowledge organization because it helps learners consider the relationships among form and function as well as the causal behaviors and mechanisms. We make SBF explicit through the use of hypermedia, organized in terms of SBF (Please insert Figure 1 here), through NetLogo simulations that make behaviors visible (Please include Figure 2a and b here) and through the ACT tool (Please include Figure 3a and b), which makes SBF explicit as students build models using the language of the SBF conceptual representation.

Along with the hypermedia and ACT tools, students also used NetLogo simulations to learn about the behaviors and functions in an ecosystem (Hmelo-Silver et al., 2007; Wilensky & Reisman, 2006). Using these simulations, (Figure 2) students had opportunities to explore factors that would affect the dynamic balance in the aquarium. For example, the macro fish spawn simulation allowed students to manipulate different aspects of the system such as initial population, spawning, filtration level, and amount of food. Thus if the students overfed the fish, then the increasing ammonia (from fish excretion) in the water would affect water quality and have toxic effects on the fish, leading to mortality. This helped problematize water quality, which is a black box in the macro simulation. This created the need for students to identify some of the invisible components within an ecosystem. For example, using the micro-level simulation, students could observe how crucial the nitrification cycle is for the overall health of an ecosystem and understand the important role that bacteria play in converting toxic forms of nitrogen (ammonia) into less toxic forms of nitrogen.

Although there was some minor variation among the four participating teachers, they followed the same general sequence. The science teachers introduced the unit by asking students to articulate their ideas about ecosystem functions, activating their prior knowledge and providing formative assessment for the teachers. The teachers then moved on to the ACT modeling tool and asked the students to represent their thoughts about ecosystems as structures behaviors and functions. The students recorded their ideas in a table within the ACT tool (Please insert Figure 4 about here). The teacher also encouraged the students to use the hypermedia to build on their ideas about the ecosystems. The teacher then had students explore the NetLogo simulations. In the simulations students, students could manipulate various ecosystem components (e.g., number of fish, amount of food, number of plants) in order to maintain a healthy ecosystem (Eberbach & Hmelo-Silver, 2010). The students worked in groups and had opportunities to refine their models. At the completion of the two-week period, students presented their models to the rest of the class.

Research Design:

A pre-post test single-group design was used for this study.

Data Collection and Analysis:

Students completed tests before and after the intervention. In completing this assessment instrument, students drew components of an aquatic ecosystem and were asked to show relationships between these components. In addition, students answered open-ended questions about different parts and processes of an aquatic ecosystem. They also solved problems related to ecosystems.

The scoring criteria for the pre and post tests are summarized in Table 1. All of the questions (17) were coded based on two different scoring schemes. The first examined student explanations of relationships between structures and their related behaviors and functions. The codes were assigned to the responses on a four-point scale, shown in the upper part of Table 1 (please insert Table 1 here).

We also coded for whether the students were able to identify and explain relationships between micro and macro elements within an ecosystem. Only eight of the 17 questions were coded for Macro and Micro (MM) level because only these questions afforded opportunities to explain both micro and macro level connections. The other questions on the assessment were specific to either macro or micro elements within an ecosystem. The micro-macro relationship score was assigned as shown in the lower part of Table 1.

The following student response on the importance of 'waste' to the aquatic ecosystem illustrates how these scoring schemes were applied. The student wrote:

> Waste is normally produced by organisms such as fish. It contains ammonia. Through the nitrogen cycle, bacteria breaks it down into nitrite then nitrate (which is a less toxic form of nitrogen), which is then used for plant growth.

The response indicates the presence of multiple structures, such as fish, ammonia, bacteria, nitrites and nitrates. We considered "waste" as a structure; we coded "bacteria breaks it down" as behavior and "which is then used for plant growth" as its function. We assigned this response an SBF relation score of 4 as the student has identified at least one structure in relation to behaviors and functions. In addition, we assigned this response the maximum score of 3 for the micro-macro coding it as reflects connecting macro (waste) and micro (ammonia, nitrogen cycle) level structures and processes. Interrater reliability was calculated by having two independent raters code 20% of the sample. The overall reliability was 87% agreement.

Findings / Results:

The results, shown in Table 2 (please insert Table 2 here), demonstrate moderate to large effects of our technology-rich curriculum intervention. These results demonstrated significant improvement in understanding SBF relationships over time (F (1, 310) = 69.58, $p < .001$). In addition to the SBF relationships, we also measured the relationships between macro and micro elements of the system. Descriptive statistics are shown in Table 2. The results from a repeated measure ANOVA found a significant gain from pre to post test, F (1, 310) = 193.30 $p < .001$).

Conclusions:

In summary, students significantly improved their understanding of the aquarium ecosystem in terms of relationships between structures, functions, and behaviors. In addition, students increased their identification of micro level structures and there was a trend toward students' articulating relationships between micro to macro level structures. It is the increase in the discussion of relationships that we argue are necessary for a more sophisticated understanding of ecosystems.

From an ecosystem perspective, the interrelationships between structural and behavioral/functional levels represent mechanistic explanations of ecological phenomena. A critical aspect of these mechanistic explanations is drawing links that are not solely linear or one-to-one. Again, previous study has found that students have a tendency to pose linear relations when representing ecosystems (e.g., Hogan 2000; Hogan & Fisherkeller 1996; Leach et al. 1996; Reiner & Eilam 2001). Perhaps the SBF conceptual tool enabled students to conceptualize at a more general level enabling more links to be made beyond lines.

Relating the invisible components in complex systems is something that middle school students find difficult (Liu & Hmelo-Silver 2009). By thinking about elements within a system using the SBF framework, micro level phenomena might be made more salient. In addition, SBF thinking provides a language by which students can both think about and describe the levels within the complex ecosystem.

A limitation of this research is the pre-post design with no comparison group. This design was chosen as a first step during iterative development as part of a program of design research. Additional analyses are being conducted to better understand achievement among different subgroups. In addition, we are in the process of qualitative analysis of both written and video data to explore how student develop their understanding of complex systems and how the technology serves to mediate student inquiry.

Our findings have implications for instruction. The SBF conceptual framework provides students with a language to express notions about complex ecosystems. Given that students have difficulty transferring ideas between one ecosystem to another, the SBF language might serve to broaden the scope of ideas a student has which, might promote abstraction of ecosystem concepts. Future directions should include design of curricula that feature other natural systems in an effort to understand how students transfer ideas. Given the value of systems understanding to ecological literacy, these investigations will be important in furthering our knowledge of how to improve teaching and learning of complex scientific phenomena.

Appendices

Appendix A. References

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Appendix B. Tables and Figures

Not included in page count.

System: Enter a description for your system here.

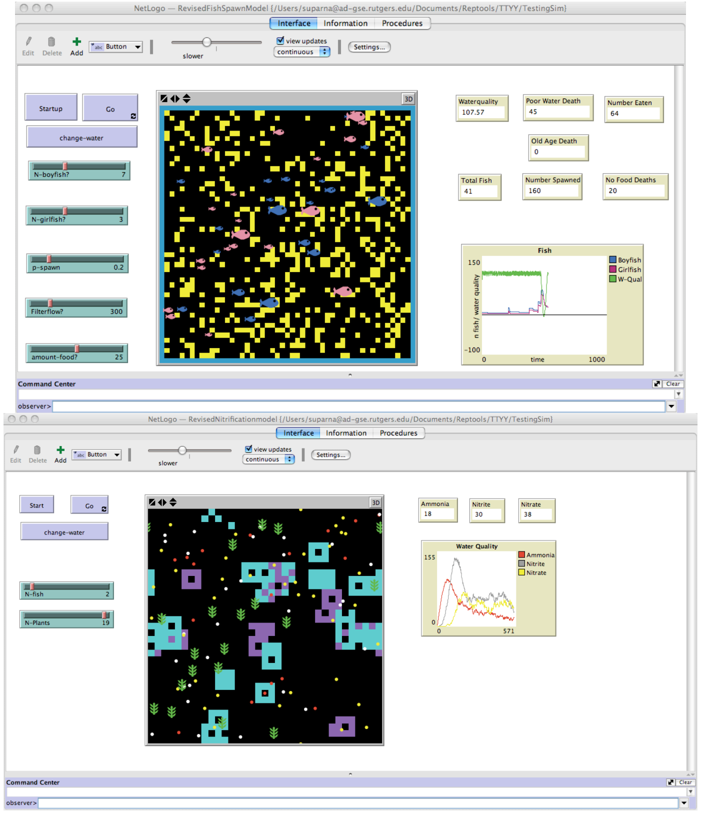
System Function:

System Behavior:

Why is it necessary to maintain a healthy aquarium?

Why do fish and other living things have different roles in the aquarium?

Figure 1. Function-centered hypermedia



N-boyfish? 7

N-girlfish? 3

p-spawn 0.2

Filterflow? 300

amount-food? 25

Waterquality 107.57

Poor Water Death 45

Number Eaten 64

Old Age Death 0

Total Fish 41

Number Spawned 160

No Food Deaths 20

N-fish 2

N-Plants 19

Ammonia 18

Nitrite 30

Nitrate 38

Figure 2. NetLogo Fish Spawn and Nitrification simulations

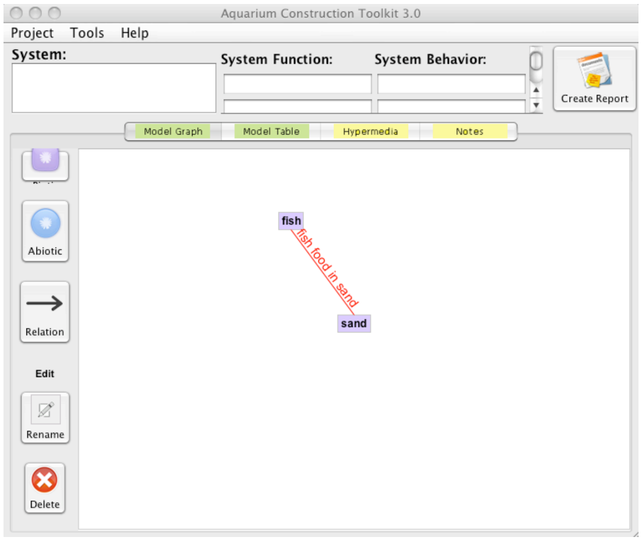


Figure 3a. ACT: A space to create models

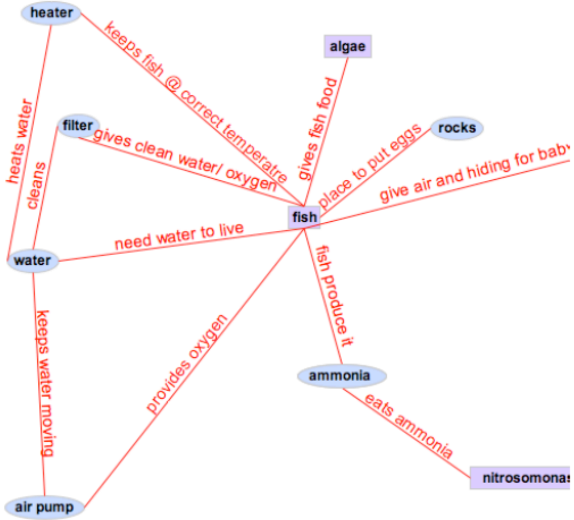


Figure 3b. ACT: Example of model created by a student.

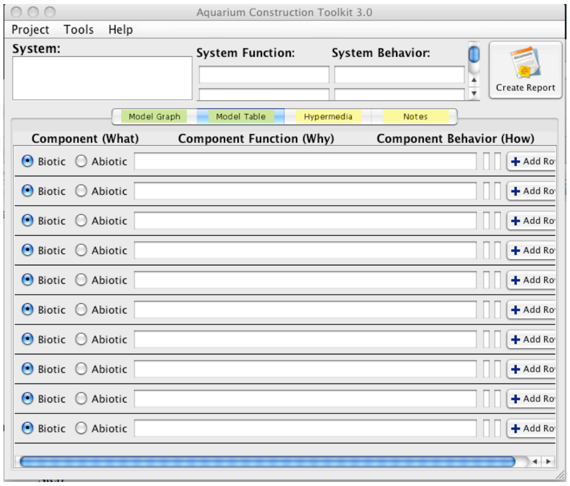


Figure 4. ACT table where students record ideas as structure, behavior, and function

Table 1. Scoring criteria for pre and post test

SBF Relation	Explanation	Score
No Answer		0
S	Identifies structure **without connecting** to other structures, behaviors, or functions. Ex: "An aquarium has fish, gravel, and bacteria." Ex: A drawing with no connections (written or drawn).	1
S:S	Identifies some relationship **between** structures. Ex: "Bacteria are in the gravel." Ex: A drawing with connections but no elaboration (written or drawn).	2
S:B or S:F	Identifies structures in relation to behaviors **or** functions. Ex: (B) "Fish eat the food." (F) "Fish get energy." Ex: A drawing with connections and elaboration (written or drawn).	3
S:B:F	Identifies structures in relation to behaviors **and** functions. Ex: "The fish eats food to get energy." Considerations: -Children may include many individual SB's and SF's, but to code an answer as SBF, the all three must reflect some relationship to each other. -SBF thinking is not necessarily represented in one sentence as the example here.	4

Micro/Macro Level	Explanation	Score
No Answer		0
Macro or Micro	Identifies **only** macro **or** only micro structures or processes.	1
Macro + Micro	Identifies **both** macro **and** micro structures or processes.	2
Macro ⇆ Micro	Identifies some **relationship between** macro and micro structures or processes.	3

Table 2. Descriptive statistics for pre and post tests (All *n*=311)

Measure	Pretest	Posttest	*d*	Range
SBF relationships	44. 64 (16.17)	54.06 (21.40)	0.58	0-98
Macro/ Micro Level	13.87 (5.12)	19.70 (8.11)	1.13	0-44