Multiple Trajectories for Understanding Ecosystems

Catherine Eberbach, Cindy Hmelo-Silver, Rebecca Jordan, Suparna Sinha
Rutgers University, 10 Seminary Place, New Brunswick, NJ 08901
catherine.eberbach@gse.rutgers.edu, cindy.hmelo-silver@gse.rutgers.edu, jordan@aesop.rutgers.edu, suparana.sinha@gse.rutgers.edu
Ashok Goel, Georgia Institute of Technology, Atlanta, GA 30332, goel@gatech.edu

Abstract: This is an exploratory study about how middle school students develop an increasingly coherent understanding of ecosystems. As part of a broader design research program, we coded and analyzed 12 middle school students’ drawings of aquatic environments collected before, during, and after a technology-rich instructional intervention. Coding considered several dimensions: relations (macro/micro, biotic/abiotic, structure-behavior-function) as well as coherence, and extraneous structures. Findings suggest that students may follow multiple non-linear trajectories towards an increasingly coherent understanding of ecosystems. Even so, the ability to observe phenomena at multiple macro/micro and biotic/abiotic levels may be an underlying constraint to also observing integrated structure-behavior-function relations and the development of a more coherent understanding of ecosystems.

Systems thinking is at the forefront of science education standards and is important for being scientifically literate citizens (Committee on Conceptual Framework for the New K-12 Science Education Standards, 2011; Jordan et al, 2009). Yet systems thinking poses many challenges for learners (Hmelo-Silver & Azevedo, 2006; Jacobson, 2001). Some of these challenges include making connections across system levels, including a system’s structures, underlying mechanisms (or behaviors), and functions (Goel et al, 1996; Hmelo-Silver, Marathe, & Liu, 2007), connecting macro level phenomena with micro level phenomena (Penner, 2001), as well as connecting a system’s biotic aspects with abiotic aspects such as sunlight (Eilam, in press; Shepardson, Wee, Priddy, & Harbor, 2007).

Although learning research has documented these challenges as well as identifying what students learn after participating in instruction about systems (e.g., Assaraf & Orion, 2005; Eberbach & Hmelo-Silver, 2010; Yoon, 2008), little research has documented the learning trajectories that students take to understanding ecosystems. Our focus here on learning trajectories is consistent with the recent emphasis on learning progressions (Duncan & Hmelo-Silver, 2009; Duschl, Schweingruber, & Shouse, 2007). In particular, Mohan, Chen, & Anderson (2009) developed a learning progression for carbon cycling. Through a cross-sectional analysis, they identified four levels that represented increasingly sophisticated reasoning. Across these levels, students’ ideas became more coherent as they progressed from informal accounts dominated by agents to more scientific accounts in which processes (i.e., matter transformation) occur at multiple levels and scales. At the lowest level, students largely generated macroscopic narratives focused on objects and events but did not observe connections between biotic and abiotic aspects. At the next level, students composed narratives of causal sequences of events, which included unseen mechanisms but did not account for constraining principles such as conservation of matter. The authors described the third level as “school science narrative about processes” (Mohan et al., p. 688), where students explained some processes in terms of chemical interactions. At the highest level—where national standards are set—students gave detailed qualitative process accounts of systems. For example, students should be able to explain organismal changes in terms of chemical processes and consistently identify materials being exchanged in living systems. It is not surprising that few students reached this highest level. In fact, most middle school students functioned at levels one and two and high school students at levels two and three.

Although Mohan et al (2009) characterize student thinking and achievement, they do not describe learning trajectories over multiple time points for individual learners, nor do they account for how different aspects of these levels develop. Often, student understanding of curricula is assessed using pre- and posttests that may not reveal detailed learning trajectories in designed settings, such as the technology-rich learning environment that is the focus of our research. This kind of testing assumes that growth is linear over time, which is not necessarily a justifiable assumption when trying to understand individual change. Consider that multiple paths may lead to the same outcome and that outcomes at a group level may be different from those that occur at an individual level (Sloane & Kelly, 2008). In a discussion about the measurement of learning progressions, Wilson (2009) notes that different dimensions of learning may be staggered, meaning that there may be different trajectories for the different dimensions.

One way to look at this kind of complex change in learning is the microgenetic method (Siegler & Crowley, 1991), which gathers detailed data from learners over an extended period to gain deep understanding.
of changes in understanding. Initially developed for laboratory conditions, Chinn (2006) argued that a microgenetic approach can be adapted for classrooms to understand the rate and timing of learning, the intermediate steps along the way, and how different changes might be clustered. To adapt this method to the classroom, the grain size must be necessarily larger and measurement occasions less dense. One approach could be through video analysis of intensive learning episodes, which is not particularly practical for capturing learning on large numbers of students. Alternatively, student performance on related tasks could be examined over multiple time points. This is the approach we adopted to explore and identify possible learning trajectories of middle school students as they learn about aquatic ecosystems.

**Methods**

This study is part of a larger program of design research that develops and explores computer-based instructional interventions that facilitate student understanding of aquatic ecosystems (Hmelo-Silver et al, 2011). To promote systems thinking in a way that enables students to think about multiple interacting components, we organized instruction around the structure, behavior, and function (SBF) conceptual representation (Goel, et al., 1996; Hmelo-Silver, et al., 2007). Doing so explicitly portrays a system’s structures (i.e., configuration of components and connections), functions (i.e., output), and behaviors (i.e. causal mechanisms that enables the components’ functions). Thus, the SBF conceptual representation functions as a lens that enable students to observe, model, and understand the relationships among form and function, as well as the causal behaviors and mechanisms of complex systems.

The context for this analysis was a five to six week enactment of a new curriculum unit on aquatic ecosystems in two middle school classrooms. The unit was organized around the problem of fish mysteriously and suddenly dying in a local pond. Students engaged in inquiry through evaluation of assorted forms of scientific evidence, the use of NetLogo simulations (Wilensky & Reisman, 2006), and the creation and revision of SBF models using the Ecosystem Modeling Toolkit (EMT) (Vattam, et al., 2011). As students used these simulations, they had many opportunities to explore factors that affect the dynamic balance in a pond and an aquarium. Students also read supporting information in the form of hypermedia text that was organized around function-oriented questions and content (Liu & Hmelo-Silver, 2009). The simulations and instruction emphasized photosynthesis, cellular respiration, and decomposition, all of which are processes critical to explaining how and why the fish died suddenly in the pond. Students learned about pond ecosystems and the aquarium as a model aquatic system in both classrooms. However, due to challenges with initially sequencing lessons in Classroom 1, we redesigned some sequences for Classroom 2. In classroom 1, students were initially presented with a problem about fish dying in a local pond followed by designing aquariums as model systems. In classroom 2, students initially designed aquariums as model systems and then were introduced to the problem about the pond.

**Participants and Data Sources**

Study participants included 12 students from two public middle school science classrooms in two schools in northeastern United States. Students were selected for this analysis because they showed improvement in articulating more complex SBF and Macro/Micro relationships at posttest. Six students were selected from both classrooms.

Data sources included student drawings from two sets of drawing assessment tasks. In all, we analyzed four drawings from each student (totaling 47 because of student absence). The first set, which was administered before and after classroom instruction, asked students to draw what happens in an aquatic ecosystem. The second set, described here as the Aquarium Assessment, was administered twice during classroom instruction. Based upon what they learned about the fish dying in the pond, students were asked how they would set up an aquarium to keep fish healthy. Both sets of drawing tasks also instructed students to draw lines to indicate relationships between parts of the drawing and to label the lines to explain why they made these connections.

Because the curriculum was modified after its enactment in Classroom 1, students completed the Aquarium Assessment at slightly different points in time. Specifically, in Classroom 1, Aquarium Assessment 1 (AA1) was implemented after introductory modeling and evidence assessment activities and EMT model revisions. Before Aquarium Assessment 2 (AA2), students revised EMT models and interacted with simulations focused on behaviors and functions of macro and micro level phenomena and nitrification simulations. In Classroom 2, AA1 was implemented after introductory modeling activities, the construction of a live aquarium model, and interactions with a simulation on carrying capacity. Before AA2, students revised EMT models and interacted with simulations focused on behaviors and functions of macro and micro level phenomena.

**Coding**

All drawings were coded along multiple dimensions to better understand how interacting components and processes may affect increasingly complex systems thinking. We developed coding along the following dimensions: Structure-Behavior-Function (SBF) relations, Macro/Micro relations, Biotic/Abiotic relations,
Extraneous Structures, and Coherence. Scoring criteria are summarized in Table 1. The first two authors discussed each student drawing and reached agreement through discussion.

Table 1. Scoring Criteria for Student Drawings

<table>
<thead>
<tr>
<th></th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
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<tbody>
<tr>
<td>Macro/Micro (e.g.,</td>
<td>Identifies only macro structures or processes*</td>
<td>Identifies both macro and micro structures or processes</td>
<td>Identifies relationship(s) between macro and micro structures or processes</td>
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<tr>
<td>fish, plants/</td>
<td></td>
<td></td>
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<tr>
<td>bacteria, oxygen)</td>
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<tr>
<td>Biotic/Abiotic</td>
<td>Identifies only biotic structures* **</td>
<td>Identifies both biotic and abiotic structures</td>
<td>Identifies relationship(s) between biotic and abiotic structures</td>
</tr>
<tr>
<td>(e.g., fish, plants/</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ammonia, sun)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SBF</td>
<td>Identifies structures without connecting to behaviors or functions</td>
<td>Identifies structures in relation to behaviors or functions</td>
<td>Identifies structures in relation to behaviors and functions</td>
</tr>
<tr>
<td>Extraneous (e.g.,</td>
<td>Includes no extraneous structures</td>
<td>N/A</td>
<td>Includes at least 1 extraneous structure</td>
</tr>
<tr>
<td>castles, divers)</td>
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<tr>
<td>Coherence</td>
<td>Phenomena is isolated</td>
<td>Single cluster covering everything or multiple disconnected clusters</td>
<td>Multiple clusters with connections among clusters</td>
</tr>
</tbody>
</table>

*Based on our observations, students only began with macro or biotic structures. **If only one abiotic structure appeared in a largely biotic scene, we coded the drawing at Level 1. A higher score represents a more desirable outcome, except for extraneous structures.

To illustrate how the coding was applied to student drawings, we examine the pre and post-test drawings of Student 1 (See examples in Figure 1). We applied the Macro/Micro code as Level 1 in the pre-test example because all structures (e.g., fish, coral, seaweed) are macroscopic, whereas the posttest example is coded as Level 3 because the student identifies relations between macro and micro levels (e.g., fish and ammonia, algae and oxygen). We applied the Biotic/Abiotic code as Level 1 in the pre-test example because the student drew a largely biotic scene and included only one abiotic structure (ocean floor). In the posttest example, we coded this as Level 3 because the student included examples of biotic and abiotic structure relations (e.g., algae and sunlight; bacteria and nitrate). In both drawings, no structures were deemed irrelevant so Extraneous Structures was coded as Level 1 for each. For SBF, the pre-test example was coded as Level 2 because the student related structure and behavior relations (e.g., starfish eats the clams; fish lives in the coral). In the posttest example, Student 1 reached Level 3 of the SBF code (e.g., sunlight causes algae to grow links to algae makes oxygen for fish). For coherence, we coded the pre-test example as Level 2 because it could be interpreted as a single cluster covering everything, whereas the posttest example was coded as Level 3 because the student included multiple connecting clusters (see SBF posttest example).

Results

Exploring Learning Trajectories in Two Classrooms

To support our analysis, we constructed two graphs (Figure 2) that depict the group means for each systems dimension in each classroom. In looking at the graph of Classroom 1, students appear to have made steady gains towards higher levels of macro, biotic, SBF, and Coherence dimensions, and essentially converging at posttest. From the start, students represented structures in terms of either their behaviors or functions and made connections between phenomena (Coherence). However, these structures were mostly macroscopic and biotic. Even so, they could articulate relationships between structures either by AA2 (Biotic/Abiotic) or by posttest (Macro/Macro). Their understanding of SBF appeared to be flat at AA1, but otherwise showed steep growth so that by posttest all students could represent phenomena at the highest level of SBF. On average, Coherence trailed all other dimensions and approached Level 3 by posttest. Finally, the inclusion of extraneous structures spiked at AA2 and then declined until no drawings included extraneous structures by posttest.
In Classroom 2, students appear to have made quick gains in the macro and biotic dimensions, but to more gradually shift to more complex representations of SBF and Coherence. Between pre-test and AA1 there is a steep change in Biotic/Abiotic and Macro/Micro structures. On average, students quickly shifted from largely macroscopic and biotic structural representations to ones that depicted relations between both Biotic/Abiotic and Macro/Micro structures. This change remains stable through posttest for the macro/micro dimension, but declined slightly for the biotic/abiotic dimension at posttest. Students started with some understanding that structures have behaviors or functions within a system. However, it was only at AA2 that modest growth in SBF was apparent, but even at posttest not all students reached the highest SBF level. Coherence also showed a relatively gentle slope that approached a mean Level 3 at posttest. Few extraneous structures were included at pre-test and no longer appeared after AA1.

Recall that each classroom experienced slightly different activity sequences. Despite these differences, certain patterns emerged across classrooms. On average, students in both classrooms started with understanding that structures have some behaviors or functions in a system. Students made more complex connections between macro and micro structures as well as between biotic and abiotic structures before reaching the highest levels of SBF or Coherence. Thus, from these graphs, we might expect that before students observe more complex relations between structure, behavior, and function, they need to “master” connections among other system levels. Finally, Coherence did not perfectly track any one dimension, suggesting that Coherence detects something different from SBF.

Individual Student Learning Trajectories
Until now we have only considered the mean classroom learning trajectories, but this level of analysis is only part of the story. What of individual student trajectories? Visually inspecting the trajectories of Student 1 and Student 2 (Figure 3) reveals that there can be considerable variability in the paths that individual students take to achieve the same endpoint. In the case of Student 1, it is evident that while starting with a mid-level understanding of SBF, these are limited to macroscopic and biotic structures, possibly with no particular connections. By AA2, the student has reached the highest levels on all dimensions, but still included some extraneous structures. In comparison, Student 2 has also started with a mid-level understanding of SBF and has also focused largely on macroscopic and biotic structures, but could identify mid-level coherent relationships between the structures. By the AA2, this student also reached the highest levels of Biotic/Abiotic, Macro/Micro structure relations, but it was not until posttest that the student could also represent SBF and Coherence at the highest levels as well. Unlike Student 1, this student never included extraneous structures in any of the assessments.
Looking more closely at the assessment drawings of Student 1, we see that the student begins by working at a simple macroscopic level and is focused on biotic structures only (Figure 1, left). As the student moves from AA1 (Figure 4, left), his/her drawing reflects connections among Macro/Micro and Biotic/Abiotic levels. Structures remain connected to overall behavior or function, but elaborated mechanisms do not yet appear. Additionally, decorative elements (i.e., castle) have entered the picture. In AA2 (Figure 4, Right), which was completed after the students engaged in modeling activities and simulation-supported inquiry, connections between SBF appear in the drawing. Although the castle is still present, we note that it is now in the background. There is also an increased level of connectedness within the drawing that persists to the posttest (Figure 1, Right). In addition, the posttest includes key ecosystem processes such as photosynthesis.

Although space does not permit detailed qualitative analyses, we found that assigning thematic narratives to student drawings to be a useful lens for characterizing shifts in student conceptualizations of ecosystems. Student 1’s drawings are typical. At pre-test, the dominant narrative “habitat” depicts a static set of structures with fixed relations. In comparison, the posttest narrative “dynamic processes” depicts ecosystems as being driven by processes, such as photosynthesis and cellular respiration that both affect and are affected by changing conditions across multiple levels.
Discussion

We conducted an exploratory study of how middle school students develop coherent understanding of a natural system, using aquatic ecosystems as an example. Students’ drawings were generally the most coherent when they made connections across all levels. Even so, both classes showed a dip in understanding biotic and abiotic relations at posttest after making gains through AA2. This is a good reminder that learning does not always happen in linear patterns and that different dimensions of learning may have different paths (e.g., Wilson, 2009). Likewise, new transitional knowledge can sometimes be fragile (e.g., Siegler & Crowley, 1991). There also seems to be a lot that can be learned by studying the variability among individual learning trajectories. At the same time, the findings suggest that there are potentially foundational dimensions—Macro/Micro and Biotic/Abiotic relations—that are necessary for learning about aquatic ecosystems. Ongoing analyses of a more heterogeneous sample also suggest that students who stalled at mid-levels of Coherence included macro and micro as well as biotic and abiotic components, but seldom in relation to one another. Moreover, those students who start at moderate levels of Coherence or SBF typically include macro and biotic components only. This may be the start of a learning progression for ecosystems that could be empirically validated in the future. Additional investigations might examine whether students include relationships between levels of Macro/Micro and Biotic/Abiotic structures because these are relatively easier to achieve or because they are prerequisites for
observing dynamic processes that require integrating across levels and developing higher levels of SBF thinking and Coherence.

Figure 4. Drawings by Student 1 for Aquarium Assessment 1 (top) and Aquarium Assessment 2 (bottom).

These findings are encouraging, but much more work is needed before drawing firm conclusions. Future analyses will include a larger and more diverse sample. However, we now have preliminary evidence that these dimensions may provide a plausible account of student learning by adapting microgenetic techniques to the classroom. This illuminates how changes in systems thinking may occur in a technology-rich inquiry environment.
References


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