From tacit knowing to explicit explanation: Mining student designs for evidence of systems thinking

Abstract: In this paper we examine what students can learn about systems when they engage tasks that require systems thinking to support their successful completion. Specifically, we document what students know about systems that they can explicitly state as well as what they can demonstrate that they know tacitly through their designs. In contrast to most existing approaches to teaching students about systems, which involves teaching students explicitly about systems, this paper considers data from a project that sought to support students' nascent understandings of systems thinking by engaging them in experiences that would support their tacit understanding of principles of systems thinking. Analyses of students' systems thinking leverage both emergent understandings of what systems thinking looks like, as well as building on coding schemes used by others.

Introduction and Framing

It has become increasingly clear that students' experiences in schools do not match the kinds of experiences they are likely to have once they have completed school. The push to support "21st century" skills stems from this mismatch, and which skills need supporting is the topic of significant conversation. In this paper, we focus on one particular aspect of 21st century skills, which involves understanding the world not as a simple set of cause-and-effect experiences, but rather as a set of complex systems. Systems thinking generally refers to a way of understanding the world as a set of systems that are made up of many elements, each of which have distinct behaviors, which change and interact, giving rise to emergent behavior. The advantages to understanding the world as a set of systems are many, but a chief advantage is that systems thinking allows students to understand and interpret the world across content areas (Goldstone & Wilensky, 2008). Unfortunately, supporting students to develop systems thinking has proven to be a significant challenge. First, systems thinking ideas are difficult (Hmelo-Silver & Pfeffer, 2004) and is also often counter-intuitive (Wilensky & Resnick, 1999). Systems thinking requires students to look for myriad contributions to system behaviors as opposed to simple cause and effect. Indeed, a key concept of systems thinking involves understanding that a small change can lead to a significant outcome—an idea that flies in the face of many core assumptions we have about the world. Linda Booth-Sweeny (2001) points out that most of our experiences in the world, particularly as children, are explained in terms of causality, and we have very few opportunities to experience the world as a set of systems.

Despite these challenges, the advantages to supporting students to understand something about systems are clear. The open question is how to best go about doing it. The purpose of this paper is to examine what students can learn about systems when they engage tasks that require systems thinking to support their successful completion. Specifically, we are interested in documenting what students know about systems that they can explicitly state as well as what they can demonstrate that they know through their designs (what some might argue is more tacit understandings). In contrast to most existing approaches to teaching students about systems, which involves teaching students explicitly about systems, this paper considers data from a project that sought to support students' nascent understandings of systems thinking by engaging them in experiences that would support their tacit understanding of principles of systems thinking. We begin by briefly reviewing what is known about how to best support students' thinking about systems, and situate the curriculum studied in this paper as that context. We then share our analyses of students' systems thinking, leveraging both emergent understandings of what systems thinking looks like, as well as by building on coding schemes used by others.

Teaching students about systems

Jacobson and Wilensky (2006) provide a review of studies on student learning of systems thinking ideas and their respective implications for potentially useful pedagogical approaches to teaching them. They argue that, "students need opportunities to experience complex systems phenomena in ways that will let them enhance both their ontological and conceptual understandings" (p.19). Research has suggested several pedagogical approaches hold potential in supporting the development of students' systems thinking skills, most of which focus on student learning in the context of science. For example, student engagement with agent-based manipulative models of emergent phenomena have proven useful in helping students to think and reason about complex systems (Wilensky, 1996). Likewise, participatory simulations can offer students opportunities to sharpen or develop systems thinking heuristics (Abrahamson & Wilensky, 2005; Goldstone & Wilensky, 2008). Moreover, participatory simulations provide an opportunity for students to recognize and grapple with flawed inclinatory reasoning often responsible for students' misconceptions of the interconnections between micro- and macro-level perceptions (i.e. emergence; a vital conceptual aspect to systems thinking) (Wilensky 2005).

This research points to the importance of offering opportunities for students to experience aspects of systems for themselves (either by playing a role of an aspect of a system, or experimenting with elements of a system). This is especially useful in pushing students' thinking beyond a simple cause-and-effect and helping them understand that a small change in one component can lead to an entire disruption of the system. This doesn't jibe with many of our direct experiences or the stories we know (Booth-Sweeny, 2001). Indeed, most of the stories that students (and adults) hear about the world around them involve simple cause-and-effect, and such causal thinking seems to dominate the reasoning of students and adults alike. An additional challenge in this work is that much of the existing activities about systems thinking are grounded in the sciences, and thus require that students understand both the scientific content as well as systems thinking ideas.

This paper considers how to support students to develop ideas about systems through engaging them in design activities that can create grounded opportunities to develop nascent understandings of key principles of systems thinking. This approach draws first on the idea that students might be better equipped to reason about systems in relation to a content with which they are already familiar. It also draws on recent research that including students in design activities can create a useful framework for supporting systems thinking (Hmelo-Silver, Holton, & Kolodner, 2000; Torres 2009). Hmelo-Silver, Holton, and Kolodner (2000) note that "design activities are particularly well-suited for helping learners understand systems because of their emphasis on functional specification and their requirement that behavior be implemented" (p. 251). Specifically, the act of design (rather than simply playing or using someone else's design) attunes the designers to both particular decisions (elements of the system) and the impact of changing the behavior of those elements. In addition, and recursive nature of design allows the designer to play and experiment with many interconnections between elements and observe their resultant impact on the larger system.

What does systems thinking look like in designs?

The process of design, with its emphasis on experimentation and analysis, creates unique opportunities to observe the behavior of a system. The process of design is likely to support the development of tacit knowledge, knowledge that one acquires unintentionally, unconsciously, or implicitly; a form of knowledge that is considered to be the foundation of innovation (Bereiter & Scardamalia, 1993; Nonaka & Takeuchi, 1995). However, most studies on children's understandings of systems thinking have focused on measuring children's *explicit knowledge* of systems as opposed to their tacit knowledge. Engaging children in designing video games offers unique opportunities to teach children systems thinking and assess children's understanding of systems.

Though Polanyi (1966) suggested, "we can know more than we can tell" almost five decades ago, researchers have, until recently, favored displays of explicit knowledge over tacit knowledge. According to Duguid (2005), implicit and explicit knowledge are a continuum, and that tacit pre-understanding (predispositions) is the basis of all understandings. Designing allows students to externalize their developing understanding of systems because the activity of designing requires children to think simultaneously of both the whole game as a system and its interacting parts. Stahl (1993) argues that computer representations are a form of explicit knowledge. From this perspective, the games children design can also be considered as a form of explicit knowledge, and used to gain insights into how children are thinking about systems. In fact, the analysis of children's descriptions of their games and the designed games itself together can illuminate the gaps in children's thinking and help inform instruction to teach children systems thinking.

This paper presents a case-study analysis of two students engaged in a video game design unit using a platform called *Gamestar Mechanic.* Our goal is not to demonstrate the efficacy of the unit for supporting all students to engage in systems thinking. Instead, this study is exploratory in that it interrogates what kinds of thinking about systems might be possible in the context of designing video games. In what follows, we present details about the study and methods of analysis, and detail what we can say about students' tacit and explicit understanding of systems theory concepts both from their designs and from interviews about their designs.

Methods

This paper focuses on two intentionally selected cases that present a contrast between ways that students demonstrated their understanding of systems. The cases are drawn from a project that examined how students engaged systems thinking concepts across different design-based modules. This study took place in the context of a two-week summer camp in a major city in the Midwestern United States. This camp was free to all students, but was voluntary, and thus students who participated in the camp had chosen to be there.

The cases

The four cases from this study were selected for closer observation in the context of data collection based on initial observations of their engagement in the module; because part of the data collection methodology involved interviewing students, cases were initially selected based on observations of who would be talkative in those interviews. From those ten cases, four were intentionally selected for further analysis based on indicators that they had some understanding of elements of systems thinking, and based on interesting contrast between what their designs illustrated about their tacit understanding of systems versus what they could say explicitly about systems. The purpose of this analysis it to tease out and characterize what students' thinking about systems looks like in the context of game design, and thus it was important to focus on cases that demonstrated some kind of engagement with those core ideas. This paper, because of space constraints, presents two of those four cases: two boys who were between the ages of 11-13.

Students were working on designs in the context of a module that focused on how to design videogames as an explicit focus; a secondary focus of the unit involved thinking of games as systems, and considering how to design well-functioning systems. Language of game design was overlapped with language of systems thinking. Students were thus introduced to the idea of systems thinking in the following terms: systems are made of up *elements*, which have particular *behaviors*, whose *interactions* shape and change the behavior of those elements and the resulting *emergent dynamics* of that system.

Data Sources

Data come from students' designs and interviews with the students about those designs. Although students designed a range of games in the context of the unit, for this paper we have chosen to focus on a final design, which involved modeling a predator-prey system. Students were taught what a predatory-prey system was based on reviewing videos of predator-prey relations, an activity that lasted approximately twenty minutes. Thus the purpose of that activity was not to ensure that students had a deep understanding of the system of predator-prey, but rather to provide a vision of the kind of system they were being asked to model. Students were free to design the game as they saw fit, and the range of designs indicate that students felt quite free to use their imaginations. Students could use any components they desired in creating their system (blocks, different "enemy" sprites, sprites that matched predator with prey, goals, points, time limits, etc.). Most students leveraged the predator-prey sprites for their design, but then ranged dramatically with respect to other elements of their games.

Coding

Two methods of coding were leveraged for this analysis. First, videotapes and designed games were reviewed using an emergent coding approach. This involved the research team watching a video of the designed games being played, and then reading through transcripts of interviews with the students about their designed games. This initial coding phase was concerned with characterizing students' thinking about their games, particularly with respect to the key ideas about systems that were covered in instruction. This process resulted in coding categories that documented: the *number of components* included in a design; the *number of interactions among components* included in the design, and evidence of *intentionality* (with respect to the design of interconnections among components). We then examined the existing literature to consider what other indicators of systems thinking had been developed. We leveraged the coding scheme from Jacobsen (2001) that included eight categories, four of which were reflected in our data. The final coding scheme (including, for the sake of space, only codes that were reflected in the data) can be seen in Table 1.

Table 1. Coding Categories

Code	Description
Number of components	Simple count of the number of distinct components in design
Number of interactions among components	Student makes connection between components explicit or comment shows implicit understanding of interaction b/w components
Intentionality	Student shows intention to alter (or include) some behavior of a system component to impact interconnection with other element(s).
Control is decentralized, based on system interactions	Student shows understanding that amount of challenge/difficulty /time arises through system interaction b/w multiple components
There are multiple causes for outcomes, rather than single	Student attributes two or more components as causes for a given observed aspect of the game.
A small action can have a significant effect	Student conveys understanding that a particular feature or aspect of agent behavior contributes to larger pattern/aspect of the game.
Agent actions can be random and unpredictable	Student recognizes when behavior of component(s) or interaction b/w components in the game can vary

We then used these final codes to look for instances in each student's interview or game. In this case, we were not interested in documenting the number of times an utterance was coded for each student, as frequency was not a particularly useful indicator of one's understanding of a particular idea. Instead, three coders reviewed all games and all transcripts and noted instances where any code might apply. The three coders then compared their instances of each code in order to ensure that the codes were being used consistently. Finally, a table was generated to document which indicators of systems thinking were present for each student.

Results

The results of our coding is presented in two parts: what can be said about students' tacit understanding based on the games they designed, and what can be said about their explicit understanding based on interviews conducted with the students about their games.

Tacit understanding

Students' designed games reveal quite a bit about what they (at least tacitly) understand about systems, and looking comparatively across the two games helps to highlight particularly significant differences. Figure 1 depicts a game designed by Levon. Each element of the game is labeled with a letter; in total his game included seven elements. The system interactions (i.e. the elements whose behaviors interact) are generally relatively simple; there are four interactions and they are relatively simple cause and effect. There is evidence of intentionality with respect to designing for interaction; all "prey generators" (element B) are located in the corners, while all "predator generators" (element A) are included in the middle of the space. Likewise, all food (element D) for the prey is located on the perimeter, near the prey generators. Based on this game, we could conclude that this student appears to have at least a tacit understanding of fundamental elements of systems thinking, although there isn't a sense of more sophisticated understandings about the ways that systems function in general.

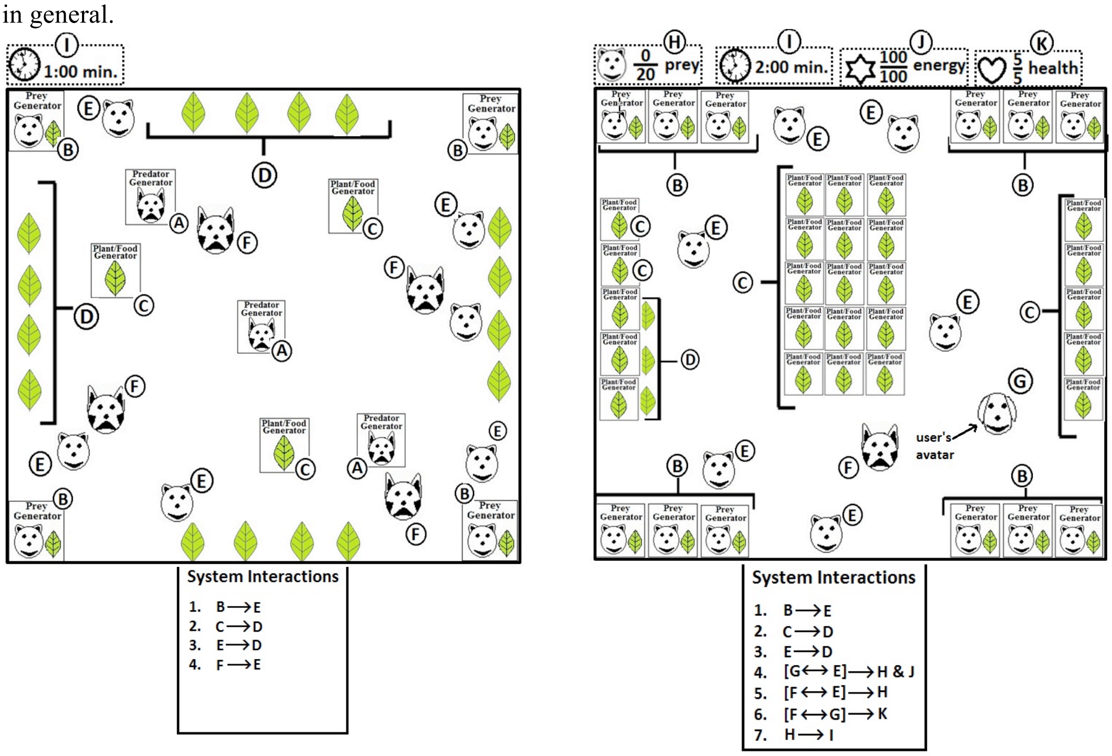

Figure 1. Levon's predator-prey game (on the left) and Waylen's predator-prey game (on the right)

Waylen's game indicates an understanding of more systems thinking concepts. His game includes more elements (ten), although the number of elements alone is not indicative of conceptual understanding. In addition, Waylen's game has almost twice the amount of system interconnection between elements, several of which represent fairly complex relationships (i.e.- shows levels of interconnection responsible for emergent outcomes for meeting the game's goals (i.e.- prey & time limit), energy, health). Taken together, this suggests that Waylen has a more sophisticated way of incorporating and planning for interaction in his design. These complex interconnections suggests that Waylen has some kind of understanding that in a system, control is decentralized and based on system interactions. There is no simple way to "win" Waylen's game; instead, myriad criteria need to be met in order for the game to be complete.

Explicit Understanding

In contrast to what students' designed games suggest about what the students understand about systems, interviews with the students, which required that they explicitly discuss their reasoning, were quite different. While Waylen struggled to describe his thinking in the context of designing his game (discussing only the simplest of interconnections between elements, which did not reflect the complexity of the game), Levon's interview revealed more understanding of systems than was suggested from his game. Specifically, in Levon's interview he described how his design worked in ways that indicated that he understood that outcomes have multiple causes, rather than single, when he described how particular interactions among components would change behaviors in the game. An example of this kind of thinking can be seen in the following excerpt:

> But, um – I see right now that I might have to change it around a little bit because if enough prey don't come out the predators won't have food to survive off of because they only eat meat….right now it will only be certain specific nashers [predators] that will survive because they [predators] eatin the prey at once. And then, so I needed to make it where the prey come out, they generate out faster than the predator to. So then they'll – the prey will be able to eat the leaves, so when the nashers come out they'll be able to the prey – so it's kind of like a chain reaction.

This excerpt also suggests that Levon understood that small changes could have a significant impact on the system, specifically in that the speed at which the prey generate impacts the potential survival of the predator, and thus the overall functioning of the system.

Conclusions

In this paper we have examined what students can demonstrate they know when they engage tasks that require systems thinking to support their successful completion. We considered differences between what students can explicitly state about what they know about systems, as well as what they can demonstrate that they know tacitly through their designs. In contrast to most existing approaches to teaching students about systems, which involves teaching students explicitly about systems, this paper considered data from a project that sought to support students' nascent understandings of systems thinking by engaging them in experiences that would support their tacit understanding of principles of systems thinking. This is exploratory work that seeks to understand what students' systems thinking might look like in this dramatically different context. However, even in this exploratory phase, two primary conclusions are clear. First, the activity of designing games can indeed support students to develop some sophisticated intuitions about systems, and second, that gaining insight into those intuitions, from the perspective of an analyst, is not a trivial task. Indeed, differences between what students can show that they know through their designs, versus what they can say that they know through interviews, suggest that assessment practices must be broad in order to capture a full picture of student thinking.

References

Abrahamson, D., & Wilensky, U. (2005a). *Collaboration and equity in classroom activities using statistics as Multi-Participant Learning-Environment Resource (S.A.M.P.L.E.R.)* Paper presented at the annual meeting of the American Educational Reserch Association, Montreal, Canada.

Bereiter, C. & Scardamalia, M. (1993) *Surpassing ourselves*. Open Court, Chicago.

Duguid, P. (2005). "The art of knowing": Social and tacit dimensions of knowledge and the limits of the community of practice. The information society, 21, 109-118.

Goldstone, R. L., & Wilensky, U. (2008). Promoting Transfer through Complex Systems Principles. Journal of the Learning Sciences, 17, 465-516.

Hmelo-Silver, C. E., Holton, D. L., & Kolodner, J. L. (2000). Designing to learn about complex systems. Journal of the Learning Sciences, 9(3), 247-298.

Hmelo-Silver, C. E., & Pfeffer, M. G. (2004). Comparing expert and novice understanding of a complex system from the perspective of structures, behaviors, and functions. *Cognitive Science, 1,* 127-138.

Jacobsen, M. J. (2001). Problem solving, cognition and complex systems: Differences between experts and novices. *Complexity, 6*(3), 41-49.

Nonaka, I. & Takeuchi, H. (1995) *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation*. New York: Oxford University Press.

Polanyi, M. (1966). The tacit dimension. Garden City, NY: Doubleday.

Stahl, G. (1993). Interpretation in design: The problem of tacit and explicit understanding in computer support of cooperative design. Unpublished Dissertation. University of Colorado, Boulder, CO.

Sweeny, L.B. (2001). When a butterfly sneezes. Waltham, MA: Pegasus Communications

Torres, R. (2009). Using Gamestar Mechanic within a nodal learning ecology to learn systems thinking: A worked example. *International Journal of Digital Media and Learning*, *1*(2).

Wilensky, U. & Resnick, M. (1999). Thinking in levels: A dynamic systems perspective to making sense of the world. *Journal of Science and Technology, 8(*1), 3-19.

Wilensky, U. (1996). Modeling rugby: Kick first, generalize later? *International Journal of Computers for Mathematical Learning. 1(*1), 124-131.