Supporting Teacher Understanding of Systems and Systems Thinking

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Abstract

The Next Generation Science Standards emphasizes students' understanding what constitutes a system and being able to reason about variables that influence the outcomes of natural systems and functions of man-made systems. However, teachers need to understand these constructs in order to teach them effectively. We designed and implemented a 3-day professional learning (PL) experience to build elementary teachers' understanding of systems and systems thinking (ST) using a conceptual change approach. The PL emphasized developing teachers' ability to identify key components of systems and ST and distinguish between systems and cycles, develop their confidence to integrate systems and ST into instruction, and support their integration of and ability to assess ST. Teachers engaged in modeled lessons, learning from a systems engineer, and lesson planning with feedback. Teachers' understanding of systems and ST and confidence for teaching ST improved, and they reported that ST was important to include in instruction following the PL. Teachers reported modeled activities, discussion, and creating and receiving feedback on lesson plans to be the most valuable components of the PL. Several implemented the lesson plans they developed during the PL with positive student outcomes in terms of engagement and conceptual understanding.

Instruction

Understanding what constitutes a system and being able to reason about variables that influence the *outcomes* of natural systems and *functions* of man-made systems is a critical 21st-century skill (Batzri et al., 2015). At its simplest, a system can be defined as identifying the *physical boundary* of the system, *structures* within the system, the *behavior/actions* of the structures, *interactions* between structures, *inputs* to the system, *outputs*, and the *function* of the overall system. Additional components can be considered, including *temporal boundaries*, *feedback loops*, and *subsystem*s (Evagarou et al., 2009). Systems thinking (ST) allows citizens to make important decisions, including how to reduce urban flooding (Fick et al., 2021), maintain sustainable aquariums with living organisms (Hmelo-Silver, Marathe, & Liu, 2007; Vattam et al., 2011), and generally understand complex natural systems more deeply (Rates et al., 2016).

As a result of growing recognition of the importance of ST across disciplines and in man-made and natural systems, the Next Generation Science Standards (NGSS) emphasizes teaching systems and ST to students at all grade levels and highlights “systems and system models” as one of the crosscutting concepts (NGSS, 2013). Students are likely to have greater interest in STEM fields such as systems engineering with repeated and increasingly complex engagement in systems-related instruction starting in elementary school. Systems engineers are pivotal in maintaining effective infrastructure, informing environmental solutions, and contributing to national security solutions. However, teachers need to understand systems and ST to be able to effectively integrate them into instruction.

Research suggests that teachers may not understand systems and are not confident in implementing ST in their instruction (Hmelo-Silver, Marathe, & Liu, 2007; Yoon et al., 2016). For example, elementary teachers often conflate cycles with systems (Maeng et al., 2024). While cycles themselves are not systems, they are indeed part of systems, and cycles are influenced by interactions in systems (Assaraf & Orion, 2005; Curwen et al., 2018; Zangori et al., 2015). Teachers may also overlook interactions and functions. While elementary teachers overwhelmingly recognize the need for students to be able to engage in ST, they indicate ST is either appropriate or very appropriate to include in elementary STEM instruction while also noting their limited confidence in teaching ST (Maeng et al., 2024). That teachers perceived ST as appropriate to incorporate in instruction provides a positive foundation for STEM educators to work from, given the recent push for teachers to learn more about ST and include it in ST instruction (Fanta et al., 2020; Fick et al., 2021; Gilissen et al., 2020; Rosenkranzer et al., 2017; Semiz & Teksoz, 2020). When teachers perceive value in a concept or pedagogy, they are more likely to adopt it and foster it in their instructional practices (Ertmer et al., 2012).

Science educators are well-positioned to support preservice and in-service teacher understanding and integration of ST in methods courses and through professional learning (PL). We developed a 4-day Systems Thinking Summer Institute (STSI) PL experience that used a conceptual change approach to support elementary teachers’ understanding and integration of ST. The STSI aligned with effective PL design principles (Darling-Hammond et al., 2017) and included explicit modeling of effective ST pedagogy; implemented active learning opportunities; was content relevant; fostered collaboration; elicited and attended to teacher beliefs; and offered sustained support during the academic year (e.g., Luft & Hewson, 2014; Penuel et al., 2007; Supovitz & Turner, 2000; Zangori & Forbes, 2014).

Professional Learning Activities

The activities were originally implemented with 10 inservice elementary teachers during the 3-day STSI with academic year support (Table 1). Teachers were from 9 schools (n = 3 town, n = 2 suburban, n = 5 rural). Teachers taught grades 2 (n = 1), 3 (n = 1), 4 (n = 3), 5 (n = 4), K-5 gifted (n = 1), and a K-4 integrated STEM elective (n = 1).

The learning objectives of the STSI were to (1) build inservice elementary teachers' understanding of systems and ST through scaffolding and a conceptual change approach with a specific focus on developing their ability to identify key components of systems and ST and distinguish between systems and cycles; (2) develop elementary teachers' confidence to integrate systems and ST into instruction; (3) support elementary teachers' understanding how to scaffold ST and modify rubrics to assess ST.

Table 1
Day-by-day Overview of STSI activities

	Day 1 Intro to systems and system components	Day 2 What is ST? How can we use technology to support ST?	Day 3 Assessment for ST
Morning	Preassessment What is a system? Modeling a man-made system	Careers and ST: Engineering guest speaker Systems vs. cycles: Modeling a natural system	Lesson planning: Developing activities to support ST
Afternoon	Modeling a man-made system (continued) Where are systems in the state standards and NGSS?	Modeling systems via simulations and programming technologies Lesson planning: Developing learning objectives for ST	Developing assessments and using rubrics to assess ST Lesson planning

Importantly, throughout the PD, teachers had opportunities to step out of the "learner" role to discuss and consider from a science educator's perspective how they can implement or modify the modeled activities for their own context. Below, we describe the daily activities during the PL.

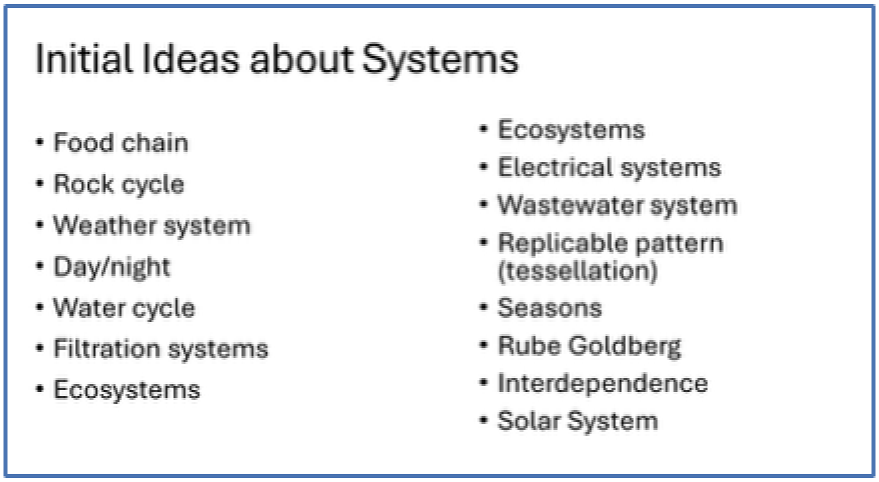
Day 1

This day focused on eliciting teachers' initial understandings of systems and ST using a preassessment, an overview of ST and modeling, a modeled activity, and reviewing where systems and ST occur in their grade-level science standards.

Elicit Initial Understandings. We began by asking teachers to complete a ST preassessment (see supplemental files). As teachers completed the preassessment, we circulated and looked at their responses to ascertain their initial understanding of systems and ST. While we did this during the STSI, this could have been done in advance. This assessment was also done at the end of the week to measure immediate learning.

Then, we facilitated an interactive discussion to elicit participants' understanding of systems. First, we shared an image of the life cycle of a butterfly, showing only the egg, larva, pupa, and butterfly Figure. Teachers were asked to discuss at their tables if the image represented a system and why or why not, or if they were unsure and why. Then, we asked teachers to identify anything they believed to be a system (Figure 1). Questions included "What is a system? What comes to mind when you hear this word? What are some systems you have taught about?" If there was a lack of agreement regarding whether something on the list was a system, we highlighted these ideas to return to throughout the STSI. This list served as an additional record of initial understandings and a resource to revisit at the end of the STSI.

Figure 1
Teachers' Brainstorming Initial Ideas of Systems

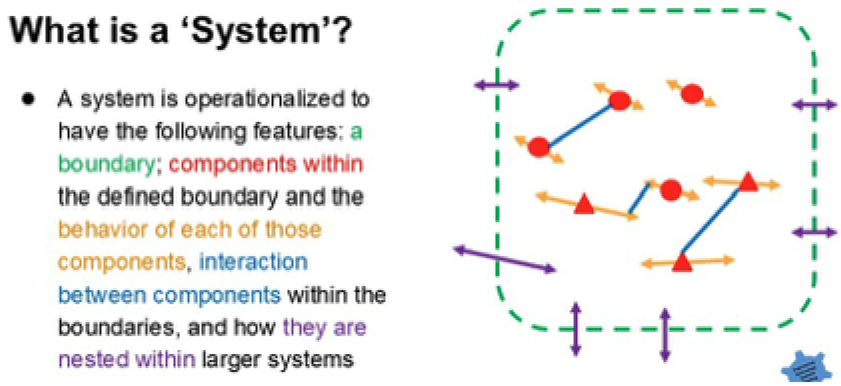


Systems Thinking and Modeling Overview. Following system list development, we gave a brief overview of systems grounded in NGSS and Fick et al. (2021). Specifically, we defined a system as:

"A system is operationalized to have the following features: a boundary; components within the defined boundary and the behavior of each of those components, interaction between components within the boundaries, and how they are nested within larger systems, and can carry out functions its individual parts cannot."

Key components of the definition were identified and demonstrated in a model through a color-coded diagram using PowerPoint slides (Figure 2). Through this example, teachers considered how a real (natural or man-made) system could be modeled using arrows, lines (dotted and solid), words, and/or shapes.

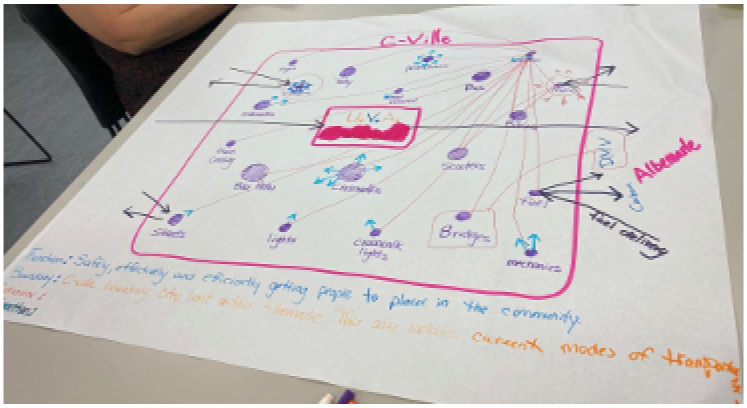
Figure 2
PowerPoint Slide Diagramming a System



Modeled Activity: Transportation System Model. In general, people are familiar with transportation systems, so we used this to model first for teachers to show how they can select a familiar system to scaffold initial access to ST for their own students. During this activity, teachers worked in groups of three to select and draw a model of one of their hometown's transportation systems (Figure 3). We asked teachers to include a boundary, system components, inputs, outputs, and interactions, and summarize the system's function. This activity helped the teachers engage in ST within a familiar, man-made context and apply the introductory information on systems.

Figure 3

Teacher Drawing of a Transportation System



Systems and ST in the Standards. Next, we introduced the teachers to the NGSS Crosscutting Concept of Systems and Systems Models using Appendix G (NGSS, 2013, p. 7-8). While our state does not use NGSS, there are clear places in our state science standards where connections to systems and ST can be made. We felt that introducing them to the NGSS framework and the ST-related learning progressions would be useful in helping them analyze our state standards for systems and ST.

Next, we grouped teachers from the same grade level to review and analyze their grade-level science standards to find standards that included systems and ST. In these groups, teachers then shared ideas about how to include more explicit connections to systems in their instruction around each standard. For example, the 3rd-grade teachers noted that one of their standards was to "develop a model (e.g., diagram or simple physical prototype) to illustrate a proposed object, tool, or process" and, after doing the transportation and butterfly models, that standard was a natural place they could engage students in ST. They also noted that they could engage students in ST to meet the standard: "The student will investigate and understand that aquatic and terrestrial ecosystems support a diversity of organisms. Key ideas include a) ecosystems are made of living and nonliving components of the environment, and b) relationships exist among organisms in an ecosystem."

Day 2

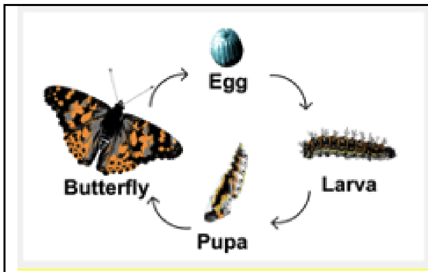
This day focused on helping teachers understand how scientists and engineers use ST in their careers, distinguishing between a system and a cycle, and writing high-quality standards-aligned learning objectives around systems and ST. This last activity served to support teachers in beginning to develop a lesson plan they could teach during the academic year that incorporates ST.

How Scientists and Engineers Use ST. To help teachers understand the value of ST skills from any everyday and career perspective, an environmental systems engineer worked with the teachers. First, he asked teachers to consider examples where ST is used in the real world. They responded with examples like "city planning," "my school district," and "in my family to help things run smoothly ."The engineer then overviewed his job as an environmental systems engineer and described how he uses ST to specifically help companies develop products that minimize impacts on the environment or have net positive effects. To help teachers understand how this is accomplished, he used two examples. The first example was a product life cycle analysis of Levis® 501® jeans. The second was an impact analysis of timber harvested for home construction that considers how inputs to a system become impacts. These examples not only attended to identifying system aspects at different points along the product's life cycle (e.g., inputs, outputs, system boundary, interactions) but also included the perspectives and interests of key stakeholders in the process (e.g., company CEO, consumers, company employees, the environment).

Modeled Activity: Distinguishing Between Cycles and Models. Next, we used a conceptual change approach to model how a cycle can be taught about using a systems lens. Conceptual change is an instructional model that consists of three phases. First, the teacher pre-assesses student preconceptions. Then, the teacher engages students in activities that are targeted to help the students confront new information that does not fit with their initial conceptions (conceptual conflict). Through discussion and reflection, the teacher facilitates the recognition of the need for modification. In the final phase, the teacher engages students in additional activities and reflection designed to facilitate the development of normative scientific conceptions (Nussbaum & Novick, 1982).

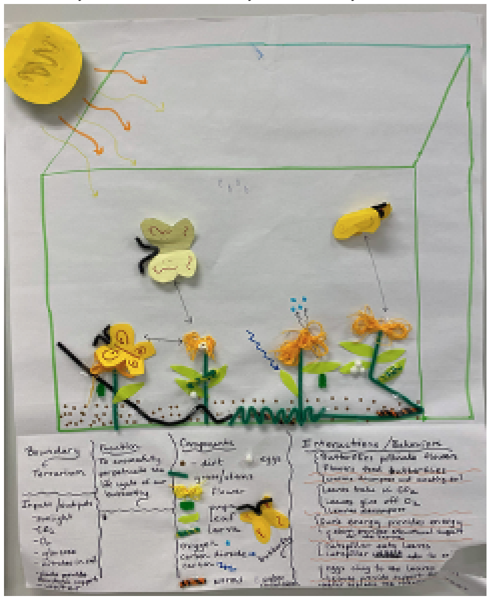
As we anticipated, teachers included several natural cycles in the initial knowledge elicitation activity (Figure 1). To begin this activity, teachers were presented with digital images that included living and non-living aspects of the system in which the cycle occurs (Figure 4). We asked teachers to compare and contrast these images with the goal of determining whether or not they represent a system or a cycle. During this phase, we facilitated a discussion of whether the image either included or did not include opportunities for ST.

Figure 4
Natural Cycle/Systems Images



Finally, we asked teachers to work in small groups to create a model of a natural system in which the life cycle of a butterfly occurs (Figure 5). We described to teachers that, in contrast to a man-made system that has a clear purpose, natural systems do not, except to perpetuate the system.

Figure 5
Teachers' Systems Model of the Life Cycle of a Butterfly

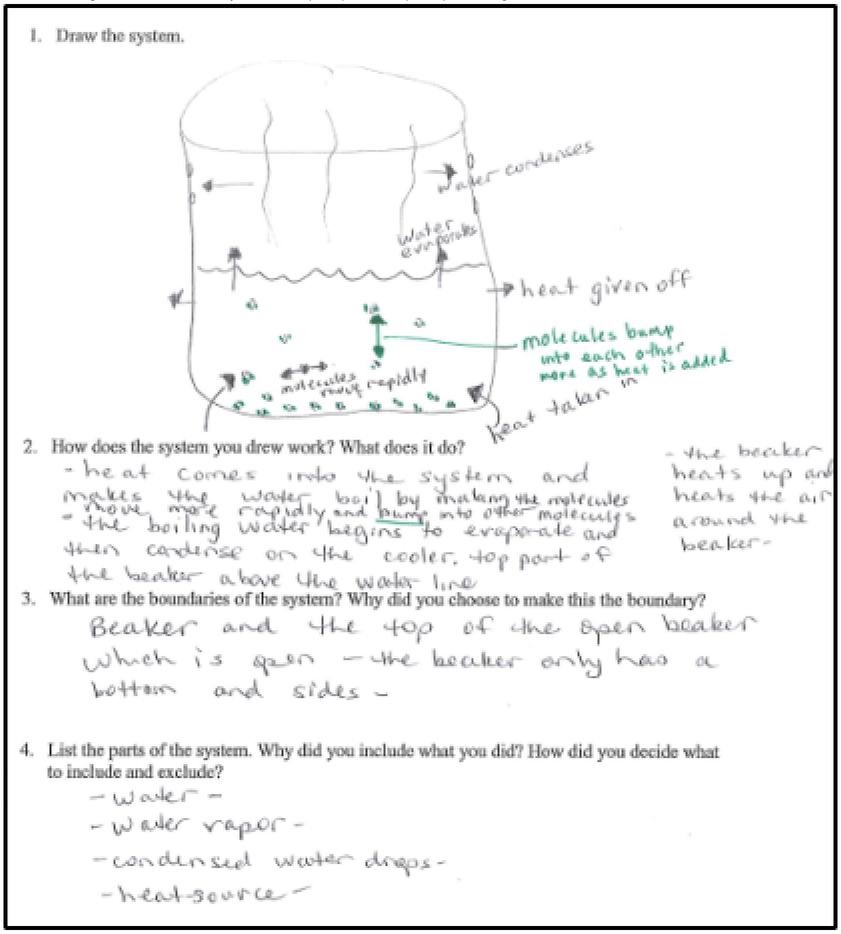


After this activity, teachers discussed how they would modify this activity for their own context. Teachers discussed using the schoolyard gardens and community gardens with which the students were familiar as a context for the activity. They also discussed how they would need to scaffold the activity for students of different grades and reading/writing abilities. For example, teachers of younger students who might not yet be readers talked about potentially using pictures (e.g., a sun, plant leaf, raindrop, butterfly, flower) for the components, inputs, and outputs, and having students glue these in place to make a system model. Teachers could also take pictures of local gardens and have students draw the system features (e.g., components, interactions, inputs) on the pictures rather than create their own models. This activity could also be used within a problem-based learning unit, the goal of which was to design a pollinator garden at the school that is welcoming to butterflies.

Modeling Systems via Simulations and Programming Technologies. A secondary goal of the STSI was to support teachers' integration of technology into instruction. To begin this modeled activity, we showed teachers a beaker of ice being heated by a Bunsen burner and asked them to draw the system given the boundary of the glass of the beaker. We chose this example because state changes are addressed in several grades of our state elementary science standards. Next, we engaged teachers in a whole group exploration of the PHET States of Matter Simulation (available at: https://phet.colorado.edu/sims/html/states-of-matter-basics/latest/states-of-matter-basics_en.html). Teachers made observations about the water particles within the beaker when heat was added. After observing the simulation, we asked teachers to add anything to their model drawings based on their observations. Additions included showing particles rather than ice cubes and arrows between particles, between particles and the container to represent interactions between them, particles escaping out of the beaker, and gas as the Bunsen burner's source of energy (Figure 6). We repeated this with a physical demonstration of a marble in a tube and the PhET Skate Park simulation.

Figure 6

Teacher Drawing of the Bunsen Burner System Before (Black) and After (Green) Observing the Simulation



Next, we asked teachers to consider how the simulation was different from the physical demonstration. Teachers responded with statements like, “You can see what the particles are doing,” and “You can change things about the system to see what happens.” We then defined a phenomena-based simulation as an “interactive, digital model that allows you to manipulate a variable and measure an outcome to better understand natural phenomena” (Gonczi et al., 2023). We described the affordances of these simulations in supporting students' ST as (1) allowing for phenomena visualization at the particle level (*structures, parts, components*), (2) allowing engagement in scientific inquiry when learning about systems (*behavior*), (3) facilitate student understanding of interactions within a system (*interactions, function*), (4) provide a common way to understand and talk about a system.

Lesson Planning: Writing High-Quality ST Learning Objectives. The final activity of day 2 was to have teachers begin thinking about a topic, lesson, or activity aligned with a systems concept that they currently teach, in which they could intentionally integrate ST. We asked teachers to identify the corresponding standards and develop ‘understand, know, and do’ objectives for the lesson, including objectives that specifically address ST. We provided examples of understand and do objectives for the modeled activities, including “changes have broad impacts,” “the universe seeks stability,” and “systems respond to changes in energy”. Do objectives included “construct and analyze a food chain that models the relationships and the flow of energy within an ecosystem” and “create a diagram that indicates the interactions between matter and energy in a beaker/Bunsen burner system.”

Day 3

Day 3 focused on continuing to support teachers in developing a lesson plan they could teach during the academic year and considering how to assess their students' ST.

Lesson Planning: Developing Activities to Support ST. As teachers developed their lesson plans, we encouraged them to consider the context that their students will be in (e.g., rural, urban; elementary, secondary) to think about accessible examples (e.g., locally relevant contexts) as well as how ST could be integrated into other disciplines (e.g., for elementary teachers, a ST lens could be used to consider historical events of interest, or even learning classroom routines) and can be used to solve everyday and complex problems. Teachers then submitted their lesson plans for feedback from the PL team.

Using a Rubric to Assess ST. Systems models that are physically or digitally created provide an opportunity to make learners' thinking visible. We developed an NGSS-aligned rubric (see supplemental files) that we created to assess ST as measured by visible elements in a systems model. Teachers used the rubric to evaluate another group's transportation model. We led a discussion with teachers on how they could use the rubric in their own instructional contexts or be of value to the teachers they interact with.

Reflections on the STSI

Results of a convergent mixed-methods study indicated significant improvement in teacher understanding of systems and ST ($z = 2.5$, $p = .011$, $r = .83$), improved confidence for teaching ST ($t(8) = 4.91$, $p < .001$, Cohen's $d = 1.6$), and that they thought ST was important to include in instruction following the PL (Maeng et al., 2024). Qualitative findings indicated that teachers reported modeled activities, discussion, and creating and receiving feedback on lesson plans to be the most valuable components of the PL. For example, one teacher described how the PL advanced their understanding of ST, “the hands-on lessons helped us explore the aspects of systems thinking and helped me realize the parts of the whole and all the components.”

Several teachers taught their ST lesson plans they developed as part of the PL in their classrooms during the academic year following PL. These teachers anecdotally reported that their students were engaged in the lessons and that they felt like their students had a deeper conceptual understanding relative to prior years as a result of teaching their lessons through a systems lens.

Conclusion

Integrating ST into science instruction allows learners to access and think about science content in a relevant and meaningful way that encourages opportunities to think about interactions between man-made and living systems and is transferable to other content areas. Natural and man-made systems are everywhere in and outside of science (e.g., government, cities, farms, families, and social networks). In the STSI, we used a conceptual change approach to model learning about systems and ST in science with a transportation system (man-made) and scaffold to a natural system (butterfly garden) because these are examples that both elementary teachers and their students are likely to encounter. Teachers found these to be accessible examples and were able to translate what they learned into lesson plans that integrated ST for use in their own classroom contexts.

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