A proposed sequence for developing systems thinking in a grades 4—12 curriculum

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Barry Richmond described seven systems thinking skills needed to become a successful systems thinker. These skills are woven throughout the grades 4-12 curriculum. The seven systems thinking skills can each be further defined by three distinct levels of competence, with an increase in cognitive capability required at each successive level. A proposed sequence is presented for the skills themselves, and suggestions are given for activities at each level within the skills. Level I activities may begin with ten-year-old students, but level II activities are best mastered by the senior students (about 18 years old). More research is needed to justify the proposed developmental sequence.

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At the 1990 International System Dynamics Conference, Barry Richmond suggested a model of how systems thinking fits into the construct called critical or higher-order thinking. (See Richmond's Figure 7 at the end of this paper).

Lauren Resnick, in her book *Education and Learning to Think* (1987), suggests that there is no one definition of critical or higher-order thinking, but that it does have some recognizable characteristics, such as being nonalgorithmic, complex, capable of producing multiple solutions, involving nuances in judgment and uncertainty, utilizing self-regulation, finding structure in apparent disorder, and being effortful. This certainly sounds like the sorts of mental activity involved in systems model building, analysis, and synthesis.

Richmond's model not only attempts to embed systems thinking in higher-order thinking but also divides systems thinking into seven separate but interrelated kinds of thinking. This article proposes a modification and expansion of his model into a spiral ontogeny of how people learn systems thinking. By spiral, I mean that systems thinking is learned at a simplistic level the first time people encounter it and at a deeper level every time they try to use it.

This learning spiral draws upon the epistemological work of Vygotsky, specifically his notion of a “zone of proximal development” (see McCaslin Rohrkemper 1989). Vygotsky's theory is that people develop a deeper and richer understanding of the world (and presumably of content taught in school) as they construct their own understanding by successively doing more and more with their knowledge. Eventually, learners can do independently what they once could do only with assistance (McCaslin Rohrkemper 1989). It also draws upon the curriculum work of Bruner (1960), who suggested that a school curriculum needs to revisit content several times in a student's career, with added depth and meaning each time a student reencounters a subject.

A sequence of learning implies a sequence of teaching and planning. Therefore, a spiral sequence of curriculum structure is also proposed to develop systems thinkers.

This model and curriculum is proposed not without risks. It is risky to reduce to “procedures” any suggestions to improve education; that is the way schools have operated for decades. To do this to systems thinking would be a mistake. This is not a linear process, although language forces a linear presentation. There probably are several stocks of learning and understanding being filled through coincident flow processes. As with any model, what we have here is a simplification of the real world, not a complete description of what is really going on. What Richmond suggests is that certain kinds of thinking are emphasized during different activities

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and are central to understanding systems thinking at different times in the learning process.

The proposed sequence

The listing in Table I of the levels of activity associated with system thinking skills has emerged through four years of observations of classes and individual students as a student, a teacher, and a researcher. It appears that most people progress through the different types and levels of thinking in the order listed. With that in mind, I make the following suggestions about a systems thinking curriculum. Two important points are to be noted:

- The suggestion is not that system dynamics be a piece of content or discipline of curriculum but that it be a tool for learning, expressing, and seeking ways to improve performance and quality. Perhaps models will become as important a communication tool as writing or using numbers.
- A little of each type and level of thinking will be learned at every grade level, but the emphasis on a specific type of thinking in a developmental sequence is the important message.

This curriculum sequence starts at fourth grade (ages 10-11 in the United States) because this seems to be a logical beginning point: most schools start having children work on more complex sorts of tasks after third grade. Certainly, some sort of systems thinking is possible to teach in the lower grades, but it is not clear what that would be like. There is much more to learn about the possibilities with the primary grades, and work with a few teachers of kindergarten through grade 3 recently began in the Catalina Foothills School District in Tucson, Arizona, to see what might happen with the very young.

Structural thinking

This is one of the most natural of skills, which most people have no problem doing at a simple level. Even young children can recognize what affects what, except in complex systems or systems with significant delays. Building interdisciplinary or thematic units is a good way to help children establish and strengthen the ability to recognize the structure of relations.

Level I structural thinking should be developed in the fourth through sixth grades. Interdisciplinary units, having students make connections between various content areas, drawing simple causal loops[1], and using simple computer simulations are appropriate strategies. Level II, replacing causal loops with a paper and pencil stock-and-flow (rate-level) drawings can probably begin in the eighth grade after the first

Table 1. The seven skills of systems thinking and associated levels of activity

1. STRUCTURAL THINKING Figuring out interrelations, what affects what, where things flow, which things accumulate.
   Level I: Recognizing what affects what: simple causal relations
   Level II: Identifying stocks and flows in phenomena
   Level III: Generating detailed flow structures (adding rates, flows, converters) and maintaining dimensional consistency in model

2. DYNAMIC THINKING According to Richmond, "the ability to see and deduce behavior patterns rather than focusing on, and seeking to predict, events."
   Level I : Drawing graphs of behavior over time
   Level II: Identifying systems' goals
   Level III: Deducing the behavior of stocks and flows

3. GENERIC THINKING Looking beyond specific chains of events to identify which, if any, generic system structures are operating to generate the observed behavior. Going beyond analysis to synthesis to achieve something new. These phenomena are called generic policy structures or system archetypes.
   Level I: Understanding and using causal-loop diagrams and archetypes
   Level II: Recognizing and using stock-and-flow generic structures
   Level III: Creating systems using multiple archetypes and stock-and-flow structures

4. OPERATIONAL THINKING According to Richmond, "thinking in terms of how things *really* work—not how they theoretically work."
   Level I: Recognizing simple causal relations using real-world variables
   Level II: Building paper and pencil stock-and-flow diagrams
   Level III: Creating computer models

5. SCIENTIFIC THINKING Being able to quantify relations, accumulations, and decisions (this is not measurement). Being able to hypothesize and test assumptions and models.
   Level I : Manipulating and modifying preconstructed computer models
   Level II: Creating simple models
   Level III: Analyzing models rigorously and testing for robustness

6. CLOSED-LOOP THINKING Recognizing that the internal circular causality of cause-effect feedback, rather than external linear cause-effect relations. is responsible for the behavior of systems.
   Level I: Identifying simple internal causal relations
   Level II: Running microworld case studies with in-depth debriefing and analysis
   Level III: Creating computer models

7. CONTINUUM THINKING Recognizing that continuous processes, rather than discrete events and classes of objects, characterize most real-world phenomena. This is difficult to do, because language and ways of seeing the world habitually emphasize discrete events and relations.
   Level I: Identifying simple continuous processes in daily events
   Level II: Manipulating, modifying, analyzing, and discussing preconstructed computer models
   Level III: Creating computer models

curriculum spiral has occurred. Level III is best started in high school, when computer modeling begins. Based upon our experience at Orange Grove, the expectation that students will create a meaningful computer model and not just use the software is appropriate for only about 1-3 percent of the middle school population at present. It is possible that with the students coming up now, who have three to four years of system dynamics experience, this percentage may increase.

Dynamic thinking

Dynamic thinking is best strengthened after people have had some practice in deducing the structure of systems. Recognizing the causes of behavior leading to a series of events is not necessarily intuitive, and in many cases, as Jay Forrester (1975) says, the pattern is counterintuitive. On a very basic level for students, recognizing the two basic components of all systems (positive and negative feedback, or balancing and reinforcing loops) that cause changing behavior is a major breakthrough in systems understanding. Once students desire to move beyond simple causal loops, though, computer models become necessary.

Although level I dynamic thinking can be started in earlier grades, a serious effort in having students develop dynamic thinking skills can best be begun in the seventh grade. Picking the behavior patterns out of popular press articles on current events and drawing simple three- or four-loop diagrams, simple computer models and simulations, playing systems role games and explaining the game in terms of behavior patterns are appropriate strategies. Level II can begin in eighth or ninth grade with simple computer model use. Advanced dynamic thinking can only be understood after several experiences with building models. Therefore, the eleventh and twelfth grades are the recommended grades for level III.

Generic thinking

This skill can only really begin to take hold after people have enough experience with deducing the dynamics of various systems so that they can recognize recurring patterns in events and in causal-loop and stock-and-flow diagrams .

Level I generic thinking can be initiated in sixth grade, but eighth grade may be when most people have had enough prior experience with dynamics to be able to find or understand generic patterns. Using causal-loop archetypes both within and between content areas, identifying similarities in the behaviors of social, natural, and mathematical systems, using simple computer models and simulations for various contents are appropriate strategies. Level II is most appropriate when modeling becomes part of the curriculum in the tenth through twelfth grades. Level III is best introduced as part of the modeling process in eleventh and twelfth grades.

Operational thinking

This type of thinking is appropriately expected when people start making serious models of phenomena. These models are not necessarily computer-based for levels I and II. But computer models do contain an element of rigorous thinking absent from mental and causal-loop models and are essential for level III.

By working with causal-loop models in sixth through eighth grades, people have been introduced to level I operational thinking, but some misconceptions can occur if causal loops are not used carefully. *Simple* stock-and-flow model building and manipulation should begin in the ninth and tenth grades for level II. This will require that teachers have some grounding in modeling and operational thinking themselves. Level III can begin in earnest in grade 11 with more complicated computer models.

Scientific thinking

This skill is best strengthened after people master operational thinking to some degree. Computers make scientific thinking accessible to more students than formerly because they can test out the mathematical results of their assumptions without possessing unusual mathematical ability.

Level I scientific thinking can be introduced in tenth grade and developed through graduation. There is much to be learned by modifying and manipulating preconstructed computer models. Having students generate their own models of systems is critical for levels II and III. By this time, students should be able to explain their assumptions and the structure and dynamics of their model, and they should be able to identify the important leverage points. Teachers of these grades should not need more skill at modeling than freshman teachers. It may be necessary, though, to have a coach or resource for students and teachers to assist understanding of modeling and systems. Level III scientific thinking is for eleventh- and twelfth-grade students. Not only tested and revised models should be provided but also the protocols used by students in the testing process.

Closed-loop thinking

Closed-loop thinking develops as structural and dynamic thinking are practiced. As students deduce the relation between structure and behavior, they are led to realize that the forces generating behavior are internal to the system. But a deep understanding of the closed-loop nature of the world best comes from building models of personal interest to the model builder.

The first rounds of causal-loop building in elementary school will start level I closed-loop thinking. In the seventh and eighth grades, when students are exploring system archetypes and manipulating microworlds, level II will begin to develop. Level III is best developed in high school, beginning in tenth grade, as students start to build models of their own and are thus obliged to identify closed-loop relations in a set of operational statements.

Continuum thinking

This type of thinking emerges when students repeatedly find continuous processes in system archetypes and generic stocks and flows. It is strengthened and deepened when students begin to operationalize their own mental models to produce computer models that accurately represent the real world.

The first hints of level I continuum thinking are demonstrated while drawing causal-loop models in fourth through sixth grades. It is important at this stage that teachers try to direct students away from explaining newspaper articles or other media reports in terms of discrete events. They should be encouraged to seek the continuous processes behind the daily events. In seventh through ninth grades, students build level II thinking when they manipulate microworld simulations and complete multiple runs of models that clearly demonstrate continuous processes. Level III is best developed through model design and construction.

The missing component

This article does not describe specific curriculum materials, activities, or instructional objectives but rather gives general guidelines. One-day, ad hoc, stand-alone activities are unlikely to develop system thinking skills, nor will they motivate students to go beyond manipulation of software. An ongoing, thoughtful use of system dynamics tools is much more likely to achieve the learning described in this article. Again, the process must be seen as developmental and lengthy, beginning far earlier than in high school.

In general, the activities that have been most successful in generating systems thinking are authentically situated (Brown et al. 1989; Draper 1992); mindful of the sorts of deliberate or accidental academic tasks teachers set up for students (see Doyle 1983); and curriculum- and content-based rather than skill-based (Draper 1991; Draper and Swanson 1990).

Examples of broad curriculum units of study that incorporate system dynamics and require several hours or weeks to complete have been used for the past four years at Orange Grove Middle School and at many of the research sites of the STACI^{N} Project conducted by the Educational Testing Service. The use and results of these units of study continue to be documented and have been presented to the educational research community. With the increased use of system dynamics in schools, more curricula will be developed, and we will learn more about what it means to learn system dynamics.

Of course, the everyday context of schools affects any curriculum or structural innovation regardless of how wonderfully planned. A carefully planned sequence like this, if implemented fully, might provide a rich set of educational experiences for those students who stay in the same school district through high school. But those students who move out, or who move into a school with a long-term view of teaching with system dynamics, will, of course, experience something different. Those moving out will have their learning truncated if their new school system does not use system dynamics; those moving in may be with peers who have had several years of experience with this curriculum.

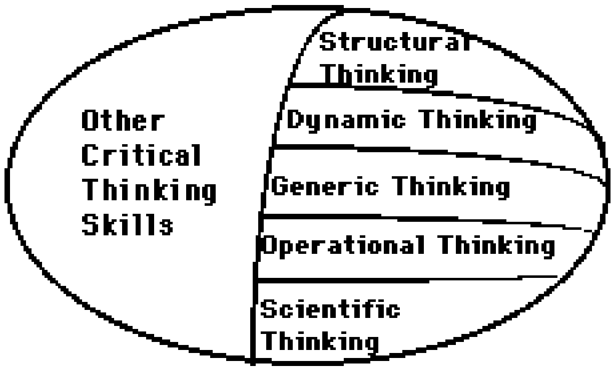
Student mobility is not the only example of why educational innovations fade; many forces act to maintain the status quo. The power of system dynamics clearly needs to be applied not only to new curriculum opportunities but also toward understanding the structures of the organizations we call schools.

An invitation to a conversation

This sequence is proposed as a stimulus for discussion. It may be that I have mismatched grade levels with skills, have jumbled the sequence, or have based the model on erroneous assumptions. Again, this sequence is not intended to be a hard-and-fast model but rather an attempt to make sense of four years of observations. I look forward to other researchers providing observational data and empirical evidence to support this proposed sequence.

Note

1. There has been excellent criticism about the use of causal loops (Richardson 1986; Forrester 1992) and the confusions that arise with the later use of stock-and-flow diagrams, especially in rate-to-level feedback relations. But beginning to understand circular causality and feedback relations, provided teachers are aware of the conceptual problems, still seems best achieved by young children with causal loops. Such relations are difficult for many people to recognize in even a simple, second-order rate-level diagram. It is important to remember that a nine-year process for children is being described here, not a quick set of workshops for adults.



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