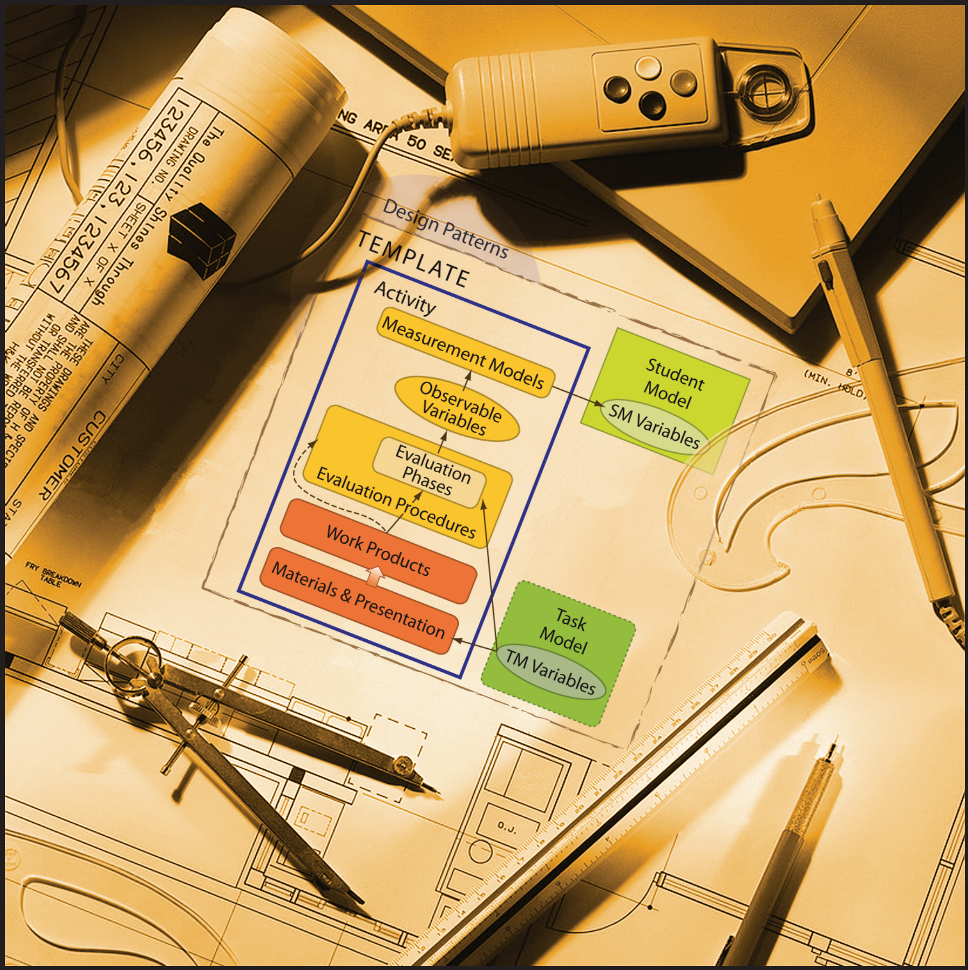

Large-Scale Assessment Technical Report 7| March 2010

Assessing Systems Thinking and Complexity in Science

Project: Application of Evidence-Centered Design to State Large-Scale Science Assessment

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APPLICATION OF EVIDENCE-CENTERED DESIGN FOR LARGE-SCALE STATE SCIENCE ASSESSMENT

TECHNICAL REPORT 7

Assessing Systems Thinking and Complexity in Science

March 2010

Prepared by:

Britte Haugan Cheng, Liliana Ructtinger and Reina Fujii, SRI International
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1. Introduction

Many scientific phenomena can be conceptualized as a system of interdependent processes and parts. The motion of the planets in our solar system, the balance of predator and prey populations in ecosystems, or the group-think of ant behavior are all systems that are well–described and taught as a group of interacting components as well as a macro phenomena that are the collective outcome of those interactions. The language of systems provides scientists and science students a means to analyze and communicate about phenomena, a useful tool in the scientific enterprise that enables recognizing how multiple factors interact and predicting patterns of change over time. Because understanding phenomena as systems, and general characteristics of systems more broadly, are important competencies that students at all grade levels are expected to develop, it is important to be able to assess these proficiencies.

Three challenges, however, face assessment designers in this domain. First, is the task of recognizing and carefully tracking task demands. While this is a challenge to all assessment design, the topic area (systems thinking and complexity, at the higher grade levels) presents an especially hard-to-understand set of ideas for both students and designers. The relevant background knowledge a designer might need to design a task in this area is significant and spread across many domains. A second challenge to assessment designers is understanding the complex relationships between systems thinking and the content or context in which the task is situated; the interplay of required and necessary, but not focal knowledge can prove difficult. And finally, designers are tasked with identifying age or grade appropriate competencies in this domain.

Addressing these three challenges, this technical report provides support for designing tasks that assess systems thinking, in the form of a design pattern. Design patterns are used in architecture and software engineering to characterize recurring problems and approaches for solving them such as Workplace Enclosure for house plans (Alexander, Ishikawa, & Silverstein, 1977) and Interpreter for object-oriented programming(Gamma, Helm, Johnson, & Vlissides, 1994). Design patterns for assessment likewise help domain experts and assessment specialists "fill in the slots" of an assessment argument built around recurring themes in learning (Mislevy, Steinberg, & Almond, 2003). The particular form of design patterns presented here were developed in the "An Application of Evidence-Centered Design to State. Large-Scale Assessments" project funded by the National Science Foundation's DR K-12 initiative.

In addition to the design pattern, a review of literature around systems thinking and complex systems is presented and discussed as the basis from which project staff developed a design pattern to support the design of assessment tasks. Section 4 of this report introduces design patterns and discusses their role in assessment design as manifest in the PADI system, an online assessment design system created as part of the now completed IERI-funded Principle Assessment Designs for Inquiry (PADI) project using a process of design argumentation, Evidence-Centered Design (Baxter & Mislevy, 2005; Mislevy et al., 2003). Section 5 discusses the relationship of themes emerging from the review of literature and their inclusion in the systems thinking Design Pattern. Also discussed is the process of using a literature review to inform design pattern development, including the organization of concepts by relevant grade levels comprising a learning progression.

2. Systems thinking and complexity in science education

While systems thinking is applicable to the study of many non-science disciplines (economics, urban planning, etc.), in the past century fields of study within science have focused on a systems perspective and several new fields of study have emerged as developments in systems thinking have evolved. The convergence of increasing computational power available to scientists, interdisciplinary collaboratories[1], and the accumulation of scientific knowledge has brought scientists the ability to study complex problems and phenomena that require systems thinking, and in many cases, the study of complexity itself. Studies of sub-atomic and quantum physics, global climate change, epidemiology, artificial intelligence, social sciences (a topic close to the authors' hearts), "chaos [theory], systems biology, evolutionary economics, and network theory"(Mitchell, 2009)are but a few of the many disciplines of science that have embraced systems and complexity as a way to build new theory, to explain otherwise intractable phenomena, and to pose innovative designs and solutions to long-standing problems.

To best provide students with a foundation for scientific literacy and to prepare students for scientific careers, fluency with systems and familiarity with complexity is now seen as essential, giving students a language and conceptual resources to bridge and induce explanations from various topic and a foundation from which to understand formalisms (Goldstone & Wilensky, 2008). Likewise, science education standards recognize the utility of teaching students about systems either as part of learning about particular phenomena or as a subject in and of itself. In addition, the pervasive applicability of systems provides a means to cohere topics across the science curriculum.

The National Science Education Standards produced by the National Committee on Science Education Standards and Assessment, a group sponsored by the National Research Council(National Committee on Science Education Standards and Assessment - National Research Council, 1996), The American Association for the Advancement of Science (AAAS) Project 2061(American Association for the Advancement of Science, 2009), and an increasing number state science frameworks efforts cite the importance of systems thinking to understanding of phenomena and to identifying commonalities across phenomena. In these frameworks, systems thinking is considered a type of literacy, much like (and related to) causal reasoning, reasoning about models or other basics of scientific practice like explanation or understanding experimentation and evidence. The first among the NSES unifying concepts and processes that undergird NSES content standards is 'Systems, order, and organization.' And in various state standards, systems thinking (which includes complexity in it's higher forms) is often cited as a common or organizing theme across domains and grade levels. In the 2009 science learning standards framework in the state of Washington, for example, Essential Academic Learning Requirements (EARLs) describe crosscutting concepts and abilities that characterize the nature and practice of science and technology. Again, the first EARL in this framework, systems thinking, "makes it possible to analyze and understand complex phenomena…systems concepts begin with the idea of the part-to-whole relationship in the earliest grades, adding the ideas of systems analysis in middle school and emergent properties, unanticipated consequences, and feedback loops in high school(Dorn & Kanikeberg, 2009)."Additionally, the states of Kansas, Minnesota, and Pennsylvania, to name a few, list systems thinking (and aspects thereof) as important across

[1] Notably, The Santa Fe Institute, founded in 1984 to bring together scientists from various disciplines to study complex adaptive systems.

grades in their standards.

To better what aspects of reasoning make up systems thinking, what challenges students face when learning about systems, and what instructional and assessment activities might address systems thinking, a review of literature was conducted across several domains; it is discussed in the following section.

3. Reasoning about Systems and Complexity

In this section, a review of literature is presented to orient the reader to the content of the systems thinking Design Pattern. This section is organized to highlight emerging themes from various information sources including, notably, the relationship between more fundamental ideas about systems and those that are prevalent in discussions of complex systems.

As mentioned in the introduction, basic understandings about systems underlie reasoning about complex ones. However, complex systems are often treated as a special case due to their emergent, adaptive character. While not necessarily producing consensus, the science of complexity and the field of complexity science are burgeoning[2]; complexity is subsequently being seen by education researchers as an important field of study despite the challenges these ideas present to students[3]. As a result, much of the literature used in this report is often focused either on systems thinking or on complex systems. However, as the purpose of the design pattern presented here is to provide support for designers assessing students' learning, topics are presented jointly, as part of a developmental trajectory or learning progression, spanning both more basic ideas which are often referred to as systems thinking and ideas related to more complex systems.

3.1 Review of Literature

The Design Pattern (shown in Appendix 1 and an interactive version available at http://ecd.sri.com), both in content and structure, was informed by a domain analysis that took the form of a literature review. An introduction to the domain was provided by senior scientists advising the project who offered direction to the literature search as well as informative references. Further references were obtained by reading through this initial set of materials and following the theoretical strands of interest. Literature included journal articles, conference papers and books (see citations list in Appendix 2).

Selecting materials that would inform the development of the Design Pattern reflected the intention to better understand the field of systems theory and complexity theory in order to extract the aspects of this broad domain critical to science assessment, enable age-appropriate assessment and expectations, identify challenges of teaching and learning complex systems (including students' documented cognitive biases and common misconceptions), and to link domain general concepts presented in systems theory and research to the content being assessed in middle school science.

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[2] Scientists are forming sub-fields in their respective domains to signify the importance of addressing issues of complexity in their work and The Santa Fe Institute was formed in 1984 to bring together scientists studying issues of complexity in various domains citing their importance to solving key scientific problems.

[3] In cognitive psychology research, it was found that students have difficulty understanding emergence, the cumulative behavior of components within a system that has no central control (Chi, 2005; Wilensky and Resnick, 1999).

A main source of information drawn upon in this literature review is the body of work around how to teach and illustrate principles of systems thinking and complexity. Instruction of systems thinking and complex systems is, not surprisingly, a complex process in and of itself often involving the revisiting of content in iterative cycles throughout a student's entire schooling career and becoming progressively more advanced. The cyclical characterization that Songer et al, (2009) used to describe learning progressions well describes the kind of trajectory implied by the literature reviewed; the cyclical nature of the learning progression is inherent in this particular paradigm of science. This trajectory is an important tool for assessment designers to have at their disposal and is therefore incorporated into the systems thinking design pattern. The following section reviews ideas from literature that are key to the science and instruction of systems thinking (Casti, 1992; Goldstone & Wilensky, 2008; Hmelo-Silver & Azevedo, 2006; Wilensky & Resnick, 1999)

3.1.1 Structural Characteristics of Systems

Interacting Components

A system is composed of interacting parts or component. Understanding how one part of a system behaves entails understanding other parts of the system. In systems of greater complexity, the system as a whole may have properties and organization that cannot be understood by studying its parts in isolation (Goldstone & Wilensky, 2008). In the literature, the parts of a system may also be referred to as components, agents and individuals.

Student's knowledge of a system is often compartmentalized, which makes systems difficult to understand as a whole or to recognize commonalities across systems. Often, components and interactions of systems are taught as two separate pieces of knowledge, with most instruction focusing on the structural aspects of a system (Liu & Hmelo-Silver, 2009), this can make it difficult for students to reason about a whole system, since they lack the knowledge of how the structure and function of the parts of a system, interact to produce the behavior of the whole system. Moreover, high-school students may learn about the role of oxygen in the respiration of food, but be unable to link this to their knowledge of the flow of matter and energy in ecosystems (Hogan & Weathers, 2003).

Students also tend to assume that the properties of a component of a system match those of the system as a whole. In children, for example, a common misconception is that molecules of a liquid are themselves composed of liquid (Hogan & Weathers, 2003). Adults have trouble explaining the wave-like macro-level property of a traffic jam, which 'moves' backwards, even though the components of the traffic jam, the cars, move forwards (Wilensky & Resnick, 1999). Related to this misconception is the finding that some high school students make mistakes in their reasoning because they incorrectly understand dynamic processes, such as the heating of metal, to be physical things, such as a substance contained in the metal (e.g., "hotness"). This has been referred to as an error in ontological understanding (Chi, 2005).

Levels

Levels refer to the structural organization of a system (Hmelo-Silver & Azevedo, 2006), as well as the description of a system (Wilensky & Resnick, 1999). For example, the phenomenon of evolution can be described at the level of the gene, the organism, or the species; each of these levels can be considered the 'object' of interest. Description at each of these levels, although concerning the same phenomena, will differ because the focus of description, the label of 'part' and 'whole', and the behavior of components at each level varies.

One difficulty associated with reasoning about the levels in systems is being able to “shift levels” in order to match the focus of reasoning with the correct level of description (Wilensky & Resnick, 1999). For example, high-school students exhibit difficulty understanding that a group-level result requires a consideration not only at the level of the components, but also at the level that these components interact (e.g., predator-prey interactions Wilensky & Resnick, 1999).

Outcomes

In some systems, outcomes can be described by an end-state of a process or by a completed process involving the components of a system. For example, an outcome of a predator-prey system is a balance in both populations. In more complex systems it may be impossible to characterize the system as having a unified purpose (Manson, 2001) and the system outcomes are themselves understood as variables within a system (Forrester, 1994). In addition, students tend to attribute intentionality to system components. For example, students tend to consider system components as agents striving towards a goal and this can inhibit reasoning across levels, reasoning about aggregations across levels and proper estimations of system outcomes. Wilensky and Resnick (1999) report students’ dislike of randomness and chaos at lower levels, which actually affect outcomes at higher levels.

Timescale

Processes in system occur over time. As a result of feedback-loops or other phenomena systems are often characterized by processes occurring at multiple time scales. Systems that have processes and interactions occurring at different points in time may exhibit the “ripple effect”, where the effects on a system at one point in time will have a flow-on effect later in time (Resnick & Wilensky, 1998). Interacting with this dimension of timescale, is that of magnitude of action and effect: in complex systems, a small action may contribute to other interactions, resulting in a significant large-scale effect, referred to as the “butterfly effect” (Jacobson & Wilensky, 2006).

Students are often unaware or can often fail to take into account the “ripple effect”. This occurs because of a tendency to focus on short-term effects at the expense of understanding larger-scale systemic outcomes, particularly those occurring later in time (Resnick & Wilensky, 1998). In the case of the butterfly effect, many students believe that there is a linear, or proportional relationship between the size of an action and its corresponding effect, that is, small actions will cause small effects and large actions will cause large effects. This view does not hold for some complex systems, where, through non-linear interactions in a system, small actions are ‘amplified’ through the system to produce an emergent and larger-scale effect at a different point in time.

<u>3.1.2 Systems-level characteristics</u>

All systems can be described both by their structure (as discussed above) and by their modes of behavior. It is at the system behavior level of description where complex systems are most often distinguished from other simpler systems, where general system characteristics are sufficient to describe both the system structure and system behavior. For example, simple systems do not produce emergent outcomes, as will be discussed below. Therefore, as in the literature, much of the following discussion focuses on complex systems and is drawn from complexity theory.

Emergence

Considered by some researchers to be the most distinguishing characteristic of complex systems (Casti, 1992), emergence describes the macro-level patterns of a system that result from the local interactions between the micro-level components of that system (Jacobson & Wilensky, 2006). Importantly, a system's large-scale behaviors and patterns cannot be deduced by observing the lower-level non-linear and indirect interactions of a system in isolation, since these tend to be qualitatively different from the large-scale behaviors (Goldstone & Wilensky, 2008).

Middle school students have a tendency to assign causality to the macro-level pattern that they are trying to explain, even when they appreciate the concept of such behavior emerging from lower-level interactions (Jacobson & Wilensky, 2006; Penner, 2000). Spatial-dynamic dimensions of a system, such as agents' velocity or density, will trigger these incorrect "agent-to-aggregate" inferences, even when students are explicitly told the rules that direct the agents' behavior at the lower-levels (Abrahamson & Wilensky, 2005, as cited in Jacobson & Wilensky, 2006). Another bias is towards causal, linear reasoning (Hogan & Weathers, 2003). This bias makes understanding emergence problematic since such phenomena are typically characterized by a lack of such causality. Finally, the 'deterministic mindset', where phenomena are interpreted as the direct cause of an action, presents a problem for systems reasoning because of the emergent characteristic of more complex systems (Resnick & Wilensky, 1998; Wilensky & Resnick, 1999).

Adaptability

A complex system's components' behavior is often described as adaptable when changing in response to, or as a cause of, environmental conditions. A system is said to be adaptable when it exhibits what are known as self-organizing behaviors (Manson, 2001). This self-organizing activity results in macro-level patterns that can be used to describe the system as a whole (Hmelo-Silver & Azevedo, 2006). Adaptability, however, is a misnomer that implies intentionality, a problem discussed further in the section on cognitive biases. The tendency to perceive the large-scale outcome of a complex system as the direct result of the willful actions of systems' individual components also results in the difficulty associated with understanding another complex system characteristic: irreducibility. Systems exhibiting emergence can also appear to be adapting, as outcomes are not directly a product of simple, lower-level interactions and rules.

The 'centralized mindset' that assumes that every phenomena must have a 'leader' or a source of centralized control, and attribution of intentionality, are two biases which make the understanding of adaptability problematic. This is because these biases assume that the macro-level observable behavior is the result of a single decision-making component of the system and/or that each of the system components willfully modifies its own behavior to suit changing conditions.

Instability

Complex systems have different ways of behaving and interacting, both as a whole and at the level of individual components. As a result of this characteristic, a particular system may exhibit instability, in that it may change its form of interaction as a result of changes to the factors influencing such interactions. A particular system exhibiting different modes of behavior is also considered to demonstrate that system's instability. For example, the characteristic of the flow of liquid through a pipe can change from being smooth, to developing whirlpools, to becoming frothy and turbulent. In this example, these changes in behavior depend on two of the system's variables: the velocity of the flow and the viscosity of the liquid (Casti, 1992).

Irreducibility
Typically, a complex system's outcome cannot be explained by focusing solely at the micro-level of local interactions, which tend to have no linear, direct connection to the observable, macro-level behavior. Conversely, this characteristic offers the ability to describe a system's behavior at the level that tends to be most salient and meaningful. While local-level interactions of components can be simple, the difficulty of reducing macro-level phenomena down to the micro-level resides in the fact that this characteristic of complex systems is intimately linked to emergence and is best understood as one of its resulting characteristics. A system described as emergent exhibits outcomes that are not a summative result of lower-level component interactions; for the same reason these systems are also described as irreducible.

Heterogeneity
Systems can also be described in terms of homogeneity or heterogeneity - or the degree to which structural characteristics are uniform (as in a flock of birds) or various (as in a diverse ecosystem). Complex systems tend to be heterogeneous (Hmelo-Silver & Azevedo, 2006). Heterogeneity can be used to describe systems' interactions, components, outcomes, and timescales. For example, in a given system, it might be that all the interactions within a system occur at different rates or timescales. The outcomes occurring at a system level might also differ; each different in type, number and magnitude.

<u>3.1.3 Systems Instruction</u>
Interacting Components
One goal of teaching systems at the elementary school level is to help students think about whole systems in terms of their component parts, and to understand how the parts relate to one another and to the whole (American Association for the Advancement of Science, 1993). Literature from science education suggests that the context in which systems are introduced to students plays a key role in whether students will appreciate the fundamental relationships among system components. For example, Introducing systems using a function-centered representation of a system has been found to be an effective way to convey the system-as-a-whole concept to students (Liu & Hmelo-Silver, 2009). In the study by Liu and Hmelo-Silver (2009), hypermedia was used to depict two different conceptual representations of the human respiratory system. In each of these hypermedia representations, the order of delivery of the structures, functions and behaviors of a system differed. The structure-oriented representation focused first on the structures of the system, whereas the function-oriented representation made the functional and behavioral aspects of the system salient by focusing on these first and then moving on to the structure of a system in a "top-down" fashion. Students using the function-oriented hypermedia developed a deeper understanding of the concepts. Furthermore, there is evidence that young students integrate scientific principles with value judgments (Hogan & Weathers, 2003). Presenting systems concepts in accessible and meaningful contexts would allow students to be able to evaluate and therefore more readily incorporate new knowledge.

Levels
According to Wilensky and Resnick (1999), misunderstanding the concept of levels is the underlying cause of several cognitive biases that hamper student abilities to understand systems. They employ computer modeling tools, such as StarLogo, to allow students to test

their assumptions about the characteristics of complex systems and the causes of the phenomena they are working with. They also encourage the practice of explaining phenomena at different levels to gain an understanding that no one level provides a sufficient explanation of the phenomena; all levels of description each provide a crucial piece of the puzzle. The challenge to understand a system as describable at various levels underlies students difficulty in understanding various outcomes of systems (Wilensky & Resnick, 1999) and can seriously challenge students to consider system behaviors, especially complex behaviors.

Teaching about System Behavior

Research suggests the difficulty in helping students reason across levels and at the system level. This is especially true the case of complex systems. Chi (2005) describes this 'shift' in thinking as ontological, one that requires students to call upon a set of cognitive resources (definitions, experiences, beliefs, etc.) that students do not associate with the reasoning required to understand system structure or simple system interactions and processes. It is argued that because such ontological misconceptions are robust, it may well be necessary to explicitly address ontological categories during science instruction. Emergent outcomes, in particular, are seen as requiring new conceptualizations of system behaviors (Chi, 2005). Other literature suggest productive strategies to encourage students to think about emergence in complex systems: recognize that there may not be a single causal force underlying the system; make clear and put into context the idea that the properties of whole systems are usually different from those of its component parts (Hogan & Weathers, 2003); distinguishing between micro- and macro-levels of analysis; and comprehending that even small changes at the micro-level can have significant effects at the macro-level (Resnick, 1994, as cited in Penner, 2000).

Incorporating these principles into instruction can take the form of computer-based modeling, where students can test all assumptions and thus challenge their misconceptions around emergence. Modeling software includes StarLogo, which uses "turtles" that can be provided with simple rules from which complex and emergent behavior is produced. Casti (1997) describes three "would-be worlds"; computer modeling programs that are designed to create artificial systems that allow students to experience the characteristics of systems. TRANSIMS aims to model flow of traffic by taking into account living areas, work, and demographics; Tierra, provides a model of neo-Darwinian evolution; and Sugarscape is a model of cultural and economic evolution that is able to model how simple rules for individual action resemble real-life, human-motivated behaviors. Moreover the prevalent use of simulation environments to instruct systems thinking can be leveraged to support students comparison of multiple case studies of the same principle, explain the case studies to themselves or construct explicit (e.g., computational) models of the cases (Goldstone & Wilensky, 2008)

3.2 Construct Mapping

Section 3.1 above presents literature review findings in an organized fashion. Other organizations are of course possible and this presentation is selective in order to present ideas in a way readers and, in future, assessment designers will be able to navigate what is, in fact, a large and varied intellectual territory. To cull repeated or important themes from across of the various domains of literature reviewed, a construct table was formulated. This construct table sought to identify related aspects of systems thinking discussed in various terms and at various levels of analysis by researchers from distinct domains. The resulting table provided a map of important systems thinking constructs, or components of reasoning, that would become the content of the systems thinking design pattern shown in Appendix 1. The construct table is shown in Appendix 2. Table 1 below lists themes emerging from the literature review and the competencies or knowledge, skills, and abilities they suggest are essential to systems thinking. The construct table is organized by grade level (middle school, middle-to-high school, high school, and expert (above high school), mapping grade appropriate competencies, as reported by the literature cited or parallel literature from other domains.

Table 1. Systems Thinking Competencies Suggested by Domain Analysis (Review of Literature)

Construct from literature	Systems thinking knowledge, skill or ability
Interacting Components	• Ability to identify the structure of the system (including interactions and outcomes) • Knowledge of types of system interactions • Ability to identify crucial qualitative or quantitative values
Levels	• Ability to identify the structure of the system (including interactions and outcomes) • Ability to relate the scope of system and scope of reasoning
Outcomes	• Knowledge of the types of outcomes • Ability to predict the outcome of an input (change) to the system • Ability to interpret the outcome of an input (change) to the system
Timescale	• Knowledge of the impact of time scales on systems
Emergence and Adaptability	• Knowledge of the types of outcomes • Knowledge of dimensions of complexity
Instability, Irreducibility, and Heterogeneity	• Knowledge of dimensions of complexity

Evidence of the learning trajectory found across the literature review was also reflected and organized by the construct table, providing a visual overview of the materials reviewed. This stage of the review was essential in distilling the broad literature into elements that could communicate important ideas to designers via the design pattern. This distillation is especially important in the development of design patterns that describe a category of reasoning that is applied in various ways depending on the context of the task the designer chooses to articulate. Model-based reasoning is another example of this category of reasoning for which this project has developed both a general design pattern and six related design patterns to further articulate instances of model-based reasoning (model use, model evaluation, model revision, etc). These design patterns can be viewed at http://ecd.sri.com as can a technical report about their development and use.

4. Evidence-Centered Design

The design pattern described in this report supports the authoring of tasks to assess students' capabilities to carry out the kinds reasoning about systems sketched above, using the tools and concepts of an evidence-centered approach to assessment design (Mislevy & Risconscente, 2006; Mislevy et al., 2003). Messick (1994) lays out the essential narrative of assessment design, saying that we

> …begin by asking what complex of knowledge, skills, or other attributes should be assessed, presumably because they are tied to explicit or implicit objectives of instruction or are otherwise valued by society. Next, what behaviors or performances should reveal those constructs, and what tasks or situations should elicit those behaviors? (p.16).

Evidence-centered assessment design distinguishes layers at which activities and structures appear in the assessment enterprise, to the end of creating operational processes that instantiate a coherent assessment argument (as described later in this section). Table 2 summarizes the ECD layers. Design Patterns are tools for work in the Domain Modeling layer, where research and experience about the domains and skills of interest that have been marshaled in Domain Analysis (e.g., a literature review as presented in section 3.0 of this report) are organized in accordance with the form of assessment arguments.

Table 2: Layers of Evidence-Centered Design for Assessments

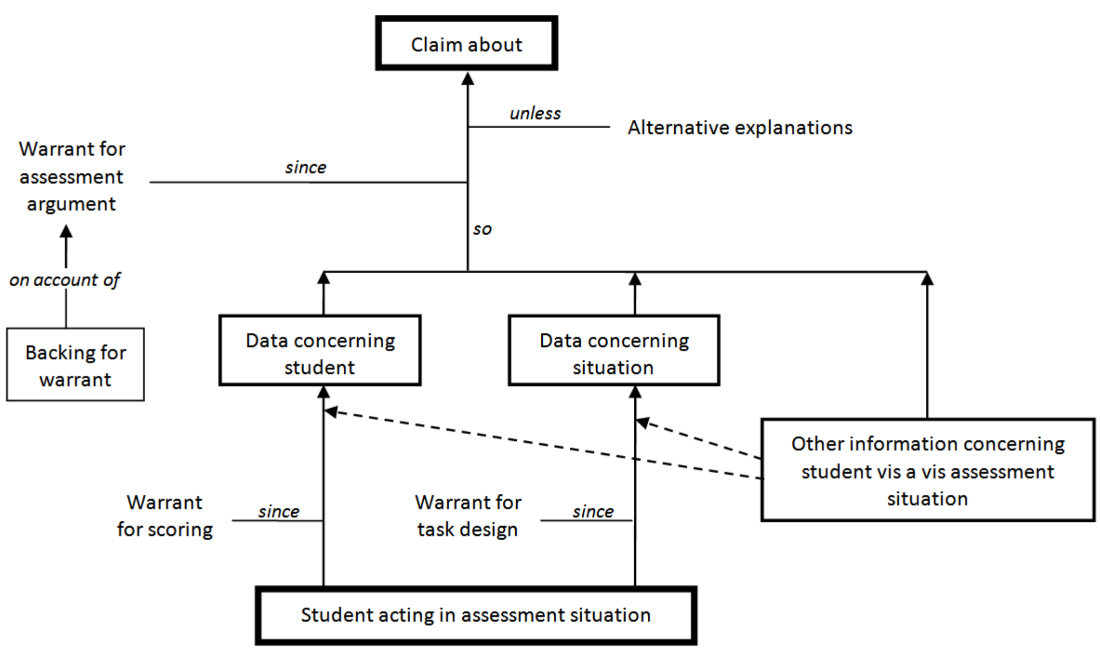
Layer	Role	Key Entities
Domain Analysis	Gather substantive information about the domain of interest that has direct implications for assessment; how knowledge is constructed, acquired, used, and communicated	Domain concepts, terminology, tools, knowledge representations, analyses, situations of use, patterns of interaction
Domain Modeling	Express assessment argument in narrative form based on information from Domain Analysis	Knowledge, skills and abilities; characteristic and variable task features, potential work products, potential observations
Conceptual Assessment Framework	Express assessment argument in structures and specifications for tasks and tests, evaluation procedures, measurement models	Student, evidence, and task models; student, observable, and task variables; rubrics; measurement models; test assembly specifications; PADI templates and task specifications
Assessment Implementation	Implement assessment, including presentation-ready tasks and calibrated measurement models	Task materials (including all materials, tools, affordances); pilot test data to hone evaluation procedures and fit measurement models
Assessment Delivery	Coordinate interactions of students and tasks: task-and-test-level scoring; reporting	Tasks as presented; work products as created; scores as evaluated

In order to show how design patterns support this work, we briefly extend Toulmin's (1958) general argument structure to the case of assessment arguments. By conceptualizing assessment as a form of argument, we can use design patterns as supports for design choices in terms of the elements of an assessment argument. For further discussion on how assessment arguments are then instantiated in the machinery of operational assessments—stimulus materials, scoring procedures, measurement models, delivery systems, and so on—the reader is referred to Almond, Steinberg, and Mislevy (2002), Mislevy, Steinberg, and Almond (2003) and Mislevy and Riconscente (2006).

4.1 Assessment Arguments

An evidentiary argument is constructed through a series of logically connected claims or propositions that are supported by data via warrants and are subject to alternative explanations (Toulmin, 1958). Figure 1 presents an evidentiary argument applied to educational assessment. The claims concern aspects of students' proficiency—what they know or can do in various settings. Data consist of their observed behaviors in particular task situations, the salient features of those tasks, and other relevant information the assessment user may have about the relationship between the student and the task situation, such as personal or instructional experience. Warrants posit how responses in situations with the noted features depend on proficiency. Some conception of knowledge and its acquisition—i.e., a psychological perspective—is the source of warrants, and shapes the nature of claims a particular assessment is meant to support and the tasks and data needed to evidence them (Mislevy, 2003, 2006). In the present case, research on systems thinking and reasoning about complex systems ground warrants; that is, why students with certain kinds of knowledge and capabilities for reasoning through particular systems would be apt to do in what kinds of task situations. Alternative explanations for poor performance are deficits in the knowledge or skills that are required to carry out a task but are not focal to the claim, such as familiarity with the computer interface used in a simulation-based investigation—"construct irrelevant" requirements, in Messick's (1989) terminology.

Figure 1: An Extended Toulmin Diagram for Assessment Arguments



4.2 Design Patterns

While Toulmin diagrams provide support for understanding the structure of an assessment argument, design patterns provide support for creating its substance. Table 3 lists the key attributes of a PADI design pattern, defines the attributes, and specifies which component of the assessment argument it concerns. Design patterns are intentionally broad and non-technical: "centered around some knowledge, skills, or abilities (KSAs), a design pattern is meant to offer a variety of approaches that can be used to get evidence about that knowledge or skill, organized in such a way as to lead toward the more technical work of designing particular tasks" (Mislevy & Risconscente, 2006, p. 72). Since design patterns do not include the technical specifics of domain content, psychometrics, or task delivery—these considerations come into play in the next layer of the design process, the Conceptual Assessment Framework (CAF)—they provide a common planning space for the various experts that may be involved in the assessment design process, such as curriculum developers, item writers, psychometricians, teachers, and domain specialists.

Using design patterns to create assessment tasks provides benefits in terms of validity, generativity, and reusability. First, validity is strengthened as tasks inherit the backing and rationale of the design patterns from which they were generated. Creating a design pattern for some aspect of proficiency requires articulating the components of the assessment argument, including the line of reasoning that explicates why certain kinds of data can offer evidence about that proficiency. The design pattern is connected to backing, or the research and experience that ground the argument. Laying out the argument frame before developing specific tasks in their particulars helps ground the interpretation of test scores. Design patterns remain a resource subsequent to task development, serving as explicit and sharable backing for those tasks.

A second benefit is generativity. Because design patterns organize experience across past research and projects that all address the assessment of some targeted aspects of learning, they support the creation of new tasks grounded in a strong line of reasoning. Organizing design patterns around aspects of learning, especially ones that are difficult to assess, helps a task designer get started much more quickly; scaffolding is provided about the shape of the argument, approaches that have been used in the past, and examples of tasks that illustrate the ideas.

A third benefit of design patterns is reusability. A design pattern encapsulates key results of work from the Domain Analysis stage and reflects the form of an assessment argument. As such it helps to structure a test designer's work in both Domain Analysis and Domain Modeling. The same design pattern can motivate a great many tasks in different areas and at different levels of proficiency, all revolving around the same hard-to-measure aspects of, say, scientific inquiry; their particulars can be detailed with the content, purposes, constraints, and resources of the assessment at hand. Moreover, one design pattern can be a starting point for creating a new design pattern that is similar, more specific, or more general than the original design pattern.

Table 3: Basic Design Pattern Attributes, Definitions, and Corresponding Assessment Argument Components

Attribute	Definition	Assessment Argument Component
Name	Short name for the design pattern	
Overview	Brief description of the family of tasks implied by the design pattern	
Use	Nature of the KSA of interest and how it is manifest. Concisely articulates the theoretical connection between the data to be collected and the claims to be made.	Warrant
Focal Knowledge, Skills, and Abilities (KSAs)	The primary knowledge/skill/abilities targeted by this design pattern	Claim
Additional KSAs	Other knowledge/skills/abilities that may be required by tasks motivated by this design pattern.	Claim if relevant, Alternative Explanation if irrelevant
Potential Work Products	Things students say, do, or make that can provide evidence about the focal knowledge/skills/abilities.	Data concerning students' actions
Potential Observations	Features of work products that encapsulate evidence about focal KSAs	Data concerning students' actions
Characteristic Features	Aspects of assessment situations which are likely to evoke the desired evidence.	Data concerning situation
Variable Features	Aspects of assessment situations that can be varied in order to control difficulty or target emphasis on various aspects of KSAs.	Data concerning situation
Examples	Samples of tasks that instantiate this design pattern	
Narrative Structures	Description of overall storyline of prompt(s) that helps to categorize and may help generate tasks	
Benchmarks	Educational benchmarks that are relevant to the design patterns	
References	Research, applications, or experience relevant to task design under this design pattern	Backing

Additional attributes can include links to other design patterns that are related to the current design pattern, for example as special-case or part-of relationships.

5. Reasoning about Systems and Complexity Design Pattern

The systems thinking design pattern is presented in Appendix 1; it is discussed in the following sections. Some exemplar tasks can be found by exploring the details links available on the 'live' version of the design pattern found at http://ecd.sri.com. The aspects of systems thinking listed in Table 1 serve as the Focal KSAs of the design pattern. As noted, they are meant to guide task design across the range of systems (or scientific phenomena) that can differ in content and detail. Content and level of detail are therefore Variable Features of tasks, and familiarity with the content and representational forms associated with particular systems is a corresponding Additional KSA. What will be common to all tasks, however, will be the Characteristic Features—those features that are essential in a problem setting in one way or another if it is to evoke evidence about the Focal KSA. To assess thinking about system outcomes for example, there must be a given system, a means to know the current status of that system (data, narrative, or otherwise), and a situation that provides a context in which to consider possible outcomes. On the other hand, such tasks may vary as to the scientific phenomena (or system) of interest and other features such as whether:

- the existing system was provided or generated by the student in earlier work;
- the task is focused on outcomes of simpler or more complex systems, those with multiple feedback loops for example;
- students are working independently or in groups; and
- the students' work takes place in hands-on investigations, open-ended written responses, oral presentations, or multiple-choice tasks.

These possibilities are highlighted for the designer in the attributes Variable Task Features and Potential Work Products.

A key assumption underlying the design pattern bears emphasis. The design pattern is constructed around aspects of reasoning, but reasoning is always about something. This is a general design pattern for creating specific tasks; that is, tasks that involve reasoning with particular systems. The terms, concepts, representational forms, and procedures associated with a system will always be intimately involved with tasks created from the design pattern. Thus substantive knowledge of the system(s) at issue is an Additional KSA in the design pattern. This alerts the task designer to important design choices concerning the interplay among the reasoning that is targeted by a task, knowledge of the components and processes of the particular system(s), and knowledge of the substantive aspects of whatever situation is presented.

5.1 Use, Focal KSAs and Characteristic Task Features

The intended use of the systems thinking design pattern is to help designers consider the range of possibilities when designing tasks to assess students' ability to reason about systems in various ways. The design pattern describes a general developmental trajectory of systems thinking as identified as part of the review of literature (section 2.0 above and mapped in Appendix 2). As such, the focal KSAs (fKSAs) articulated within the design pattern describe classes of abilities that more specific, future design patterns could unpack in more detail[4]. In addition, it should be noted that specific instances of these classes of ability are reported to occur at earlier stages than the ability to reason across the class, which occurs only at later stages of the learning trajectory implied by the literature review conducted. For example, while students in elementary school are certainly introduced to causal relationships among factors (e.g., as pollution increases, average global temperature increases), the ability to reason about types of relationships within systems (causal, taxonomic, linear, non-linear, etc.) is considered a learning objective appropriate for students at upper elementary grade levels. All fKSAs in this design pattern are articulated in this way, where the fKSA represent the ability to recognize and reason across a class or category of ideas relating to systems and the specific ideas that comprise that class are more often taught in earlier grade levels.

As the design pattern articulates systems thinking, a general family of tasks is supposed. Therefore, characteristic features are few. However, the system or systems in question (either presented to or generated by students) and the situation in which the system is being considered are characteristic in that they are necessary components of tasks that might elicit the kind of reasoning described in the design pattern. The situation or task prompt can also present important scientific content required to complete the task. Of course, the system or systems that are part of an assessment task and the context or situation in which the systems are being considered need to be coordinated by the designer to elicit the desired reasoning.

5.2 Additional KSAs

Additional KSAs are other aspects of knowledge that may or may not be involved in a systems thinking task, at the discretion of the task designer, in accordance with the context and intended use of the task. They call a task developer's attention to design choices that will intentionally elicit or minimize demands on particular systems, and on other knowledge, skills, and abilities. Primary among Additional KSAs, and essential to any systems thinking task, is knowledge of the scientific phenomena or system that will be involved in the task. The designer may, on one hand, wish to assess students' ability to describe a particular system when it is known that the students are familiar with the structure (interacting components) of that system. On the other hand, knowing both the structure of a system and being able to instantiate it in a given setting may both be of interest.

Interfaces, tools, representational forms, and symbol systems that appear in tasks can be essential to success, whether they appear as stimuli, are required in solution processes, or are needed to produce work products. A task designer interested in student reasoning about a particular system will want to use only tools and representations students are familiar with in order to avoid construct irrelevant sources of difficulty. Although it is not a focus of this technical report, we note that other enabling knowledge and skills such as language, vision, and mobility that may be required in a task are also Additional KSAs, and will need to be minimized or circumvented to improve the accessibility of tasks for students with special needs (Hansen, Mislevy, Steinberg, Lee, & Forer, 2005).

5.3 Variable Task Features

There is an important relationship in an assessment argument between Task Features, over

[4] For an example of such a family of design patterns, see the suite of 7 PADI Design Patterns about model-based reasoning and its components: model use, model articulation, model revision, etc see (www.padi.sri.com).

which a task designer has considerable control, and Focal and Additional KSAs, which are aspects of the examinee's capabilities (or lack therefore) that the task is meant to elicit. By making choices about Variable Task Features, the task designer can include or exclude features that increase or decrease the demand for Focal and Additional KSAs. This should be done in a purposeful manner. There are particular relationships between Variable Task Features and KSAs that can be laid out to support a task designer in these design decisions.
Other things being equal, the need to use a more complex system makes a problem harder. Complexity features in a system include the number of components, the complexity of their interactions, the range of outcomes possible (including emergent and adaptive outcomes), the degree to which timescales vary within the system, and the levels of description of the system that are important in reasoning through any particular task. Complexity features in a situation include the number and variety of elements in the real-world situation, the presence of extraneous information, and the degree to which elements have been stylized in order to make their identification easier.

Tasks can vary in the degree to which students are familiar with the context, in order to avoid extraneous knowledge requirements as discussed in connection with Additional KSAs, or to intentionally incorporate requirements for substantive knowledge either because it is known that students are familiar with it or because that knowledge is itself a target of inference along with the capability to reason about systems using it that knowledge. Tasks can also vary with regard to the amount of scaffolding they provide.

5.4 Potential Work Products and Observations

Because the cognitive processes involved in systems thinking is not directly visible, an assessment argument must use for data the things students say, do, or make—the work products of an assessment task. Assessment asks can be designed to elicit a variety of work products, each varying in terms of its resource requirements, knowledge demands, the aspects of thinking it can provide evidence about, and the quality of the information obtained. A related design choice is determining which aspects of work products should be discerned and evaluated. Various options, some of which are available for use with a given work product or relationships among them, are called potential observations in a design pattern. Potential Observations may be supplemented with rubrics, which, broadly construed, are the processes—algorithms, instructions, or guidelines—by which people or machines apply to work products to determine the values of observables vis-à-vis the target KSAs.

In systems thinking tasks, work products might be identification (via multiple-choice or figural response items, via written or verbal response, or via representation generation (open-ended, constructed response) of parts, interactions, or outcomes of a system. Responses might also include predications of values of particular component or outcomes.
With the availability of computer-based task administration, a wide variety of response forms can be used for students to express systems thinking in constructive and open-ended ways that lend themselves to automated scoring (Scalise & Gifford, 2006; Williamson, Mislevy, & Bejar, 2006). For example, students might be required to construct an initial rule-set that would create a simulation of a phenomenon. When the form of the work product is produced with a technology-based tool, Additional KSAs are introduced with respect to both the familiarity with the representational form and use of whatever interfaces are required. On the other hand, use of such tools can be intimately related to understanding certain kinds of systems, such as simulations of agent-based systems, such as those embodied in NetLOGO simulations, for example.

5.5 Narrative Structures
Narrative structures provide a frame for an assessment task, or set of tasks. That is, in deriving the context within which students will consider systems (in part or in whole), some 'story' or narrative devices may be more or less effective. The structure Change Over Time, for instance, is naturally suited to considering system dynamics and outcomes. Narrative structures are especially important supports for assessment designers who are constructing sets of related items, where the context of the task set needs to provide a coherent transition among individual items. As described in section 5.2 above, the context of tasks can limit, constrain, or inspire students' ability to reason about the content at hand. This is a particularly sensitive relationship when the content include systems, as system interactions and outcomes can be influenced by contextual factors.

6. Conclusion

This report has introduced a design pattern to support assessment designers creating tasks that elicit evidence of students' reasoning about systems and complexity. The design pattern serves to scaffold designers as they coordinate the demands of the tasks they create, including the enmeshing of systems thinking and science content knowledge, and as they locate grade or age appropriate competencies of this domain; the three challenges laid out in the introduction.

In addition, this report illustrates the creation of a design pattern based on a literature review. This is in contrast to surveying existing tasks and extracting information for a design pattern through task analysis. As is more common in education research, the incorporation of a learning progression trajectory makes the literature survey a necessary step in creating design pattern content. And, in cases like systems thinking where the knowledge, skills, and abilities of interest are described in multiple, often disparate literatures, a systematic review becomes all the more important.

The design pattern development process has reinforced the notion that systems thinking underlies a great deal of the science taught in every grade. That is, systems thinking appears in all science domains. As a unifying concept, systems thinking comprises a fertile topic for a design pattern, a way to consider the design of tasks that share some features and vary along other dimensions. However, systems thinking has, as a unifying concept, posed certain challenges to the development of the design pattern as well: the language of systems across domains is not consistent; what authors believe is important in systems thinking varies greatly within and across domains; and in literature where system ideas are presented in context, ideas have to be extracted and thus thoroughly understood.

Perhaps the most challenging aspect of this work has been that the task of reviewing literature and conceptualizing the design pattern is never done. Future directions for this work include extending this report to include existing and newly designed example assessment tasks to better illustrate the design pattern. And, as always, insights into systems thinking as of yet left out of this report and new insights emerging will be of interest to the project team and, hopefully, our readers.

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APPENDIX ONE: SYSTEMS THINKING AND COMPLEXITY DESIGN PATTERN

Design Pattern for Systems Thinking and Complexity | Design Pattern 2195

[View Tree | View Horiz | Duplicate | Permit | Export | Delete]

Title [Edit]

Design Pattern for Systems Thinking and Complexity

Overview [Edit]

This design pattern supports the writing of storyboards and items that address systems thinking, including complex systems. Systems are characterized as interacting component or parts. Tasks typically require multi-step causal reasoning and the consideration of the effects of multiple concepts or factors. The prevalence of scientific phenomena that can be conceptualized as systems suggests the development of a design pattern that supports the design of tasks that target systems thinking across domains and grade levels. details

Use [Edit]

U1. Because systems thinking is relevant in any content domain, this design pattern identifies common aspects of students' systems thinking that are applicable across domains and grade levels. Aspects of systems thinking are described more fully in 'Details' associated with design pattern attributes and in these examples, interactions between general systems thinking and particular content domains are described.

Reasoning about systems develops along a learning progression spanning the school years. As such, components of the design pattern are labeled to reflect the expected stage of introduction for these concepts. This categorization is intended to reflect current practice as evidenced in literature, but does not suggest a developmental pathway (i.e. what students should be expected to understand as determined by age).

For example, an important form of systems thinking, reasoning about emergent system outcomes (a dimension of complexity), is typically associated with high school science and beyond (see details link).

Grade Level Categorization:
U: upper elementary
H: high school
C: college and above details

Focal Knowledge, Skills, and Abilities [Edit]

- FK1. [U] Ability to identify the structure of the system (including interactions and outcomes) details
- FK2. [H] Knowledge of types of system interactions details
- FK3. [U] Ability to identify crucial qualitative or quantitative values details
- FK4. [H] Knowledge of the impact of time scales on systems details
- FK5. [H] Knowledge of the types of outcomes details
- FK6. [C] Knowledge of dimensions of complexity details
- FK7. [C] Ability to relate the scope of system and scope of reasoning details
- FK8. [U] Ability to predict the outcome of an input (change) to the system
- FK9. [U] Ability to interpret the outcome of an input (change) to the system
- FK10. [U] Ability to use systems to conduct investigations (including reasoning across multiple systems and/or real-world phenomena) details

Additional Knowledge, Skills, and Abilities [Edit]

- AK1. Knowledge of components/structure of the system (content knowledge) details
- AK2. Knowledge of the interactions in the system details
- AK3. Knowledge of crucial values
- AK4. Knowledge of time scales operating in system
- AK5. Ability to interpret the representation of the system details

		AK6. Scientific Reasoning details AK7. Knowledge of the nature of models (e.g., physical, formulas, 3D) details AK8. Metacognitive Skills details
Potential observations	[Edit]	Po1. Student accurately identifies components, interactions, dimensions of complexity or outcomes of a system details Po2. Student correctly labels the components, interactions, dimensions of complexity or outcomes of a system Po3. Student accurately describes the components, interactions, dimensions of complexity or outcomes of a system Po4. Student generates an accurate representation of the system (components, interactions, dimensions of complexity or outcomes) Po5. Student correctly states or identifies a predicted outcome based on system input or state change Po6. Student correctly states or identifies the results of an inquiry (i.e. the evaluation of a system as a representation of phenomenon)
Potential work products	[Edit]	Pw1. Student labels components, interactions, dimensions of complexity or outcomes of a system (e.g., physical, diagram) Pw2. Multiple-choice or other selection of components, interactions, dimensions of complexity or outcomes of a system details Pw3. Multiple-choice or other selection of whole system representations Pw4. Figural Response: Drag-and-drop of name or label of components, interactions, dimensions of complexity or outcomes of a system details Pw5. Generated text of names or labels of components, interactions, dimensions of complexity or outcomes of a system Pw6. Generated representation of system or part of system including multiple components or interactions (components, interactions, dimensions of complexity or outcomes of a system) Pw7. Student states or identifies a predicted outcome of system input or state change Pw8. Student states or identifies the results of an inquiry (i.e. the evaluation of a system as a representation of phenomenon)
Potential rubrics	[Edit]	Pr1. Dichotomous: Correct/Incorrect Pr2. Partial Credit (Identification of System Components) details
Characteristic features	[Edit]	Cf1. Representation of system (labeled image (e.g. pond ecosystem), concept map, text, equation, etc.) Cf2. Task scenario: the situation presenting task prompt, scientific content or context details
Variable features	[Edit]	Vf1. Number of system components Vf2. The number of relationships presented (given) vs. student generated Vf3. Type of relationship that is the target of the task Vf4. Prior content knowledge presented/required Vf5. Scaffolds to help students understand that there are multiple interdependent levels within a system details Vf6. Scaffolds to structure metacognitive reasoning details Vf7. Embedded support for vocabulary details
Narrative Structure	[Edit]	Cause and effect. An event, phenomenon, or system is altered by internal or external factors. The task developer shoul…

Change over time. A sequence of events is presented to highlight sequential or cyclical change in a system. Students m…

General to Specific or Whole to Parts. A general topic is initially presented followed by the presentation of specific aspects of the gener…

Investigation. Investigation itself is a narrative structure, and of course it is a natural structure for storyboar…

Specific to general and Parts to whole. Specific characteristics of a phenomenon are presented, culminating in a description of the system o…

Topic with examples. A given topic is presented using various examples to highlight the topic. For example, students are …

State Benchmarks [Edit]

MCA III: 4.1.2.1.1. Describe the positive and negative impacts that the designed world has on the natural world as more …

MCA III: 6.1.2.1.1. Identify a common engineered system and evaluate its impact on the daily life of humans. For example…

MCA III: 6.1.2.1.2. Recognize that there is no perfect design and that new technologies have consequences that may incre…

MCA III: 6.1.2.1.3. Describe the trade-offs in using manufactured products in terms of features, performance, durability…

MCA III: 6.1.2.1.4. Explain the importance of learning from past failures, in order to inform future designs of similar …

MCA III: 6.1.2.2.1. Apply and document an engineering design process that includes identifying criteria and constraints,…

MCA III: 6.1.3.1.1. Describe a system in terms of its subsystems and parts, as well as its inputs, processes and outputs…

MCA III: 6.1.3.1.2. Distinguish between open and closed systems.

MCA III: 6.1.3.4.1. Determine and use appropriate safe procedures, tools, measurements, graphs and mathematical analyses…

MCA III: 7.1.3.4.1. Use maps, satellite images and other data sets to describe patterns and make predictions about natur…

MCA III: 7.1.3.4.2. Determine and use appropriate safety procedures, tools, measurements, graphs and mathematical analys…

MCA III: 8.1.1.2.1. Use logical reasoning and imagination to develop descriptions, explanations, predictions and models …

MCA III: 8.1.3.4.1. Use maps, satellite images and other data sets to describe patterns and make predictions about local…

MCA III: 8.1.3.4.2. Determine and use appropriate safety procedures, tools, measurements, graphs and mathematical analys…

I am a kind of [Edit]

These are kinds of me [Edit]

These are parts of me [Edit]

National Educational standards [Edit]

NSES 8ASI1.1. Identify questions that can be answered through scientific investigations. Students should develop t…

NSES 8ASI1.4. Develop descriptions, explanations, predictions, and models using evidence. Students should base the…

NSES 8ASI1.5. Think critically and logically to make the relationships between evidence and explanations. Thinking…

NSES 8ASI1.6. Recognize and analyze alternative explanations and predictions. Students should develop the ability …

Unifying Concepts 1.1 - Systems, order, and organization. The goal of this standard is to think and analyze in terms of systems.

Unifying Concepts 1.3 - Constancy, change, and measurement. Some properties of objects and processes are characterized by constancy, other by change. These may …

Unifying Concepts 1.4 - Evolution and equilibrium. The general idea of evolution is that the present arises from materials and forms of the past. Equil…

Templates [Edit]

Exemplar tasks [Edit]

Online resources [Edit]

References [Edit]

Tags [Add Tag]

(No tags defined.)

List of Examples:

Activity Continuous Zone Design Pattern Educational Standard Evaluation Phase Evaluation Procedure (rubric) Materials and Presentation Measurement Model Narrative Structure Observable Variable State Benchmark Student Model Student Model Variable Task Exemplar Task Model Variable Task Specification Template Work Product

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This material is based upon work supported by NSF grants REC-0089122 and REC-0129331. For more information, see the PADI Web site.

APPENDIX TWO: DOMAIN ANALYSIS CONSTRUCT TABLE AND CITATIONS LIST

DOMAIN ANALYSIS CONSTRUCT TABLE

		Themes across Areas of Literature Review (Domains)			
	Construct Definitions (from systems theory or complexity theory)	**Aspects of reasoning (including metacognition)**	**Pedagogical themes (instructional modeling)**	**Content-embedded systems themes**	**Citation**
MIDDLE SCHOOL					
A. System Characteristics					
1. Structure					
	a) Components		Make explicit, but make sure to put into context that processes and things comprise systems and that properties of whole systems are usually different from those of its component parts (23) Using traditional approaches that presents elements of a system as a series of related and defining the parts usually doesn't lead students to understanding of the system. Learning systems as a design addresses the functional roles of the parts, the mechanisms by which those roles are carried out, and how those functions causally interact with each other. (34 cited in 9)		23, 34
	b) Interactions	Starlogo-agent-based modeling tool Students demonstrated that they were able to use agent-based modeling tool to support their reasoning and thinking about different types of CS however, their new knowledge was susceptible to reverting to noncomplex systems ways of thinking when applying new ideas they had learned to novel situations (37, 38)	StarLogoT – modelers manipulate particular entities (23)		23, 37, 38
	i. Type: Emergent/direct (a.k.a. linear/non-linear)	Challenge to learning: Tendency to interpret using linear causal models (23). Our intuition is thus counter-productive when thinking about complex systems (2)	Make explicit, but make sure to put into context that systems have emergent processes that arise from interactions of system components (23) Need to present different examples of causal templates and talk explicitly about different causal patterns (this worked when introducing h/s students to emergence) (23)	Cellular automata – used to model ecosystems, urban morphology (3, 17)	2, 3, 17, 23
	ii. Type: Recursion - feedback		Make explicit, but make sure to put into context that systems can have feedbacks in which the output from one part of a system becomes the input to other parts (23)		23

	b) Levels				
	i. Type: Micro-macro	Findings that middle school student had difficulties connecting changes at the micro-level to patterns in the global level (17)			17
	i.a) Number				
	i.b) degree	comprehend that even small changes at the micro-level can have significant effects at the macro-level (17) distinguishing between micro-macro levels of analysis (17)	explanatory modeling uses a set of rules to govern individual parts of the system use a task in which domain-specific knowledge is reduced and provides opportunities for utilizing heuristics in the development of explanation (17)	Cellular automata – used to model ecosystems, urban morphology (3, 17)	3, 17
	i.c) values				
	ii. Type: Homogenous-heterogeneous	To help students learn about systems is to keep them focused on their functional and behavioral levels rather than just on structure (7, 8, 9)			7, 8, 9
2. Outcomes					
	a) Emergent	Structures are easier to comprehend than structures and functions (8)	Structure-Behavior-Function theory (7, 8, 9) Make explicit, but make sure to put into context that effects can arise from complex interactions of multiple causal factors so that it may not always be possible to predict accurately the result of changing a single system component or connection (23) See Starlogo - http://education.mit.edu/starlogo/ and Netlogo - http://ccl.northwestern.edu/netlogo/	Human respiratory; aquarium ecosystems (8)	7, 8, 9, 10, 23
	i. Type				
	i.a) number	Students have difficulty understanding/recognizing that there may not be a singular causal force underlying the system (17)		Cellular automata – used to model ecosystems, urban morphology (3, 17)	3, 17
3. Time scale			Represent how the state of some phenomenon changes in time according to rules based on localized interaction of entities (3)	Cellular automata – used to model ecosystems, urban morphology (3, 17)	3, 17
	a) Short-term/long-term		Teaching tool: behavior-over-time diagram (23)	Story plots and characters – language arts class (23) ** see entry for high-school level physics	23
4. Bounds					
B. Reasoning about Systems					
1. Bounded			Make explicit, but make sure to put into context		23

Rationality			that systems have boundaries that delineate external systems and internal subsystems (23)		
2. Modes of Behavior					
	a) Central/Decentralized (a.k.a. Direct/Emergent)				
	b) Stability				
C. Modeling Systems/Metacognition/Pedagogy					
	a) Cross-disciplinary		Generic modeling tool: Model-It (23)	Ecosystems (23)	23
	b) Representations	Students are often introduced to CS in oversimplified static forms and schemas are formed which become difficult to correct (35 cited in 9)			9
	c) Metaphors				
	d) Modeling		explanatory modeling uses a set of rules to govern individual parts of the system use a task in which domain-specific knowledge is reduced and provides opportunities for utilizing heuristics in the development of explanation (17)		17
MIDDLE-HIGH SCHOOL					
A. System Characteristics					
1. Structure					
	a) Components	Most people understand CS as a collections of parts with little understanding o f how the system works			7
	i. Type				
	i.a) number	Students may assume that they can manipulate the outcome of a system by adding/subtracting components; number of components changes behavior of the larger system (39)		Life cycle of slime mold (39)	39
	i. Type: Emergent/direct (a.k.a. linear/non-linear)	cause and effect are not related in time and space; see notes on relevance of operant conditioning/learning paradigm (2) short-term goals inevitably linked to a long-term consequence (2) Direct and emergent processes share similarities which may confuse students, but also some differences which helps to distinguish the two (summarized in the briefs)		lay examples: drug-taking, stealing, credit cards, saving money, humanitarianism (2) examples: global climate change, risk assessment of genetically engineered foodstuffs (22) Holling (1978, 1995)	2, 3, 4, 22

		(4)		Ecosystems - fire or pest infestation as cause; redistribution of resources and connectivity as a result (3) Flow of blood in circulatory system; diffusion (4)	
	ii. Type: Recursion	iterations are required to understand reasoning faults as they are conveyed and tested through modeling (2) assist in grasping the concept of iterations that are a characteristic of some complex systems? I.e., in having the student themselves go through iterations to come to the correct model, they will have a working mental model of what an iteration is	simulation modeling (2)		2
	ii.a) #				
	ii.b) degree				
	ii.c) values	Students may not understand that the effects of feedback are limited; the output of feedback loops is constrained by the number of components (39)		Life cycle of slime mold (39)	39
	b) Levels				
	i. Type: Micro-macro	Mid-level construction – the formation of small groups of individuals. Students form these groups either by aggregating individuals or by subdividing the whole groups Students employ mid-level construction when reasoning about emergent phenomena through the process of change. Forming mid-level groups happens in two distinct modes -Bottom-up, or emergent, construction is associated with a tendency to think in terms of agent-based reasoning about CS -Top-down, or breaking down the system into smaller groups, construction is associated with less redilection toward agent-based reasoning, and may be related to aggregate reasoning in terms of averages and flows. (12). Distinction between singular/plural not sharp; rely on level of description to understand	Make explicit, but make sure to put into context that systems and subsystems interact via flows of inputs and outputs (23) Exploratory modeling – one starts with a set of simple rules which govern individual parts of a system. The results shows after the model is run, the identifiable macro-patterns. Students can focus attentions on the links between micro-level interactions and macro-level patterns (20) Use of ordinary complex phenomena in which students participate in everyday life contexts (12)	Scattering of a class in a gym lesson (39) Life cycle of slime mold (39)	12, 20, 23

		object (39)			
2. Outcomes					
	a) Emergent	Misconceptions of emergent systems are due to errors at the ontological level; emergent processes are misinterpreted as a kind of commonsense direct processes (4) Students' available domain knowledge greatly affects about any real-world system and is a central problem in understanding how they think about emergence (17)		Flow of blood in circulatory system; diffusion (4)	4, 17
	i. Type				
	i.a) number				
	i.b) degree	Many people believe there is a linear relationship between the size of an action and its corresponding effect (36 found in 10)			10
B. Reasoning about Systems					
1. Bounded Rationality					
2. Modes of Behavior					
	a) Central/Decentralized (a.k.a. Direct/Emergent)	Deterministic-centralized mindset" causes difficulty to make sense of emergent phenomena - People tend to favor explanations that assume central control and deterministic causality (37, 38, 39) and people harbor deep-seated resistance towards ideas describing various phenomena in terms of self-organization, stochastic, and decentralized processes (40, 19, 39)			37, 38, 39, 40, 19
	b) Stability				
C. Modeling Systems/Metacognition/Pedagogy					
	a) Cross-disciplinary	systems thinking is cross-disciplinary and interrelated (2)			2
	b) Representations	Spatial distribution (39)		Life cycle of slime mold (39)	39
	c) Metaphors		Textbooks focus on the structure-behavior description rather than the structure-function which would be more resistant to misconception (4)		4
	d) Modeling	deeper understanding of situation; surface features do not suffice for modeling (2) precision instead of ambiguity required for	simulation modeling (2) To have explanatory power, useful models of complex systems should be based on at least 3	Life cycle of slime mold (39)	2, 11, 39, 20

		model to work (2) mental models can be incorrect, have contradictions - test through simulation (2) Students avoided/disliked adding randomness to model – deterministic mindset (39) Students will initially think to modeling complex phenomena in a hierarchical fashion; also evident in experts when hypothesizing about this phenomena – centralized mindset (39)	assumptions and principles: - Their most important properties cannot be derived from a list of simple functional rules - Knowledge about them tends to be both situated (e.g., organized around experience as much as around abstractions) - They meaningfully capture and illuminate some properties of the world (11) StarLogo (39) Role-playing can complement/supplement computer-based modeling activities (20)		
HIGH SCHOOL					
A. System Characteristics					
1. Structure					
	a) Components	When trying to explain CS, students use: Modes of reasoning: -Agent-based – expression of rules or conditions and actions for individual behavior -Aggregate-expression of group properties, populations, and flows between groups or rates of change of a population (39)			39
	i. Type	Students misconstrue certain emergent phenomena according to the "Container view" – lower-level elements are part of the higher-level elements (39)	Give example of when container view applies and how it can be misused (39)	Correct: days, months, years Incorrect: traffic jams (39)	39
	i. Type: Emergent/direct (a.k.a. linear/non-linear)			High-leverage policies (2)	2
	b) Levels				
	i. Type: Micro-macro	When trying to explain CS, students misconstrue phenomena as applicable to hierarchical or organizational-chart view; this is symptomatic of a centralized mindset (a cognitive bias) (39)	Students need to understand that phenomena can be described at different levels of description, depending on the question of interest (39)	Predator-prey interactions; Lotka-Volterra equations (39) Evolution (39)	39
	i.a) #				
	i.b) degree				
	i.c) values	Students attempt to create group-level outcomes by focusing only on individual level – level confusion Description levels used with no focus of the interaction between them: • micro level – behavior of individual agents • macro level – group properties (39)	Understanding phenomena is possible by thinking at micro and macro levels and interactions between them (alternating between the two to understand relevant aspects of phenomena) (39)	Gene, organism or species levels when considering evolutionary variation and selection (39)	39

	ii. Type: Homogenous-heterogeneous	Students often apply a summative understanding to complex phenomena by assuming that the (upper-level) phenomena of interest is composed of the same parts found at the lower-level (39)		Traffic jams (39)	39
2. Outcomes					
	a) Emergent				
	i. Type – Ripple effect	People will fail to take into account the ripple effect, instead focusing on short-term effects at the expense of understanding larger-scale systemic changes; cognitive bias (20)	StarPeople (20)	Role-playing game of beer consumer, store owner, beer producer (20)	20
3. Time scale					
	a) Short-term	Speed distribution is less perceptually-obvious in emergent objects due to timescale interaction (39) ** compare to spatial distribution of slime mold example in middle-high-school	Teaching tool: behavior-over-time diagram (23) Modeling tools enable bridging of physics (interactions) - chemistry (properties of the whole) typical instructional division (39)	Plotting rates of flow in a physics class (23) ** see entry for middle-school language arts class Gas particles in a contained space; Maxwell-Boltzman distribution (39)	23, 39
B. Reasoning about Systems					
1. Bounded Rationality					
2. Modes of Behavior					
	a) Central/Decentralized (a.k.a. Direct/Emergent)	Novice and expert use different ontologies when constructing solutions to CS problems: Undergraduate novices were found to solve CS problems using a set of "clockwork" ontological statements such as control of a system from a centralized source of action effects as being predictable. (20, 21 found in 10) ** see expert entry for comparison			10
	b) Stability				
	c) Probabilistic/Deterministic	Make explicit, but make sure to put into context that effects can arise from complex interactions of multiple causal factors so that it may not always be possible to predict accurately the result of changing a single system component or connection (23)	Lambda calculus – a logical framework providing rules for how new entities are created and for how to simplify them to their so called "normal forms". (5)	Arrival of the fittest (Fontana and Buss) – a simulation attempting to answer the question of what is necessary and contingent about life (5)	23, 5
C. Modeling Systems/Metacognition/Pedagogy					
	a) Cross-disciplinary				
	b) Representations				

	c) Metaphors				
	d) Modeling		Modeling as a way of understanding a problem and seeing errors in thinking/understanding (2) Computer visualization allows for a visual exploration of the phenomena and of the limits of the models (22) Generic modeling tool: STELLA (science and social science dynamic processes) , e.g., Model-It – ecosystems (23)	Urban planning in which the student takes on the role of mayor (23) Fishery (23) oxygen production and population dynamics, reaction rates, acceleration, war and race riots (23)	2, 22, 23
EXPERT					
A. System Characteristics					
1. Structure					
	a) Components				
	i. Type: Mathematical attractors – values towards which a system variable tends to settle over time; catastrophic, strange (3)		poincare graph (3)	Chaos theory, catastrophe theory (3) Artificial stock market (5)	3, 5
	i. Type: Emergent/direct (a.k.a. linear/non-linear) Emergence - qualities which are not analytically tractable from the attributes of internal components; a function of synergism (3, 5)	People have strong preference for trying to find the cause behind a perceived pattern: - "lead" references – patterns arise due to the actions of a leader "seed" references – patterns arise due to some preexisting heterogeneity in the environment (19) [17's findings support 19's claim]	*Sugarscape* would-be world is able to model how simple rules for individual action resemble real-life, motivated human activity (28) Model-based learning activities (19)	Sugarscape – processes of cultural and economic evolution (28) Water is a substance with physical properties that cannot be predicted based on knowledge of its component molecules (5) Bell-shaped curve emerging from a collection of 'random' quantities (5) Cellular automata (17)	3, 5, 28, 17, 19
	i.a) number				
	i.b) degree: Internal structure – Relationships of differing strengths between component parts define the internal			Holling (1978, 1995) Ecosystems - fire or pest infestation as cause; redistribution of resources and connectivity as a result (3)	3

	structure of a system (3) (actually a characteristic of system relationships in general, not just emergent ones)				
	i.c) values				
	ii. Type: Recursion – feedback	Achieve better comprehension of iterations such as the tendency for distributed systems to follow an exponential growth curve in accuracy with each progressive iteration (25)	Fractals – self-referential patterns; scale invariance (3) Use of Bayesian inference to yield posterior distributions for unknown variables. Then model this pattern of interdependence using Bayesian network models as an example of the power of iterations draw closer approximations to result (25)	Structure of a tree, urban form, coastlines (3)	3, 25
	ii.a) #				
	ii. b) degree: Sensitivity to initial conditions - butterfly effect, non-linearity (3)			Holling (1978, 1995) Ecosystems - fire or pest infestation as cause; redistribution of resources and connectivity as a result (3)	3
	ii.c) values				
	b) Levels				
	i. Type: Micro-macro	Distinction between singular/plural nature of object is not clearly obvious; rely on question of interest to determine the level at which description will make sense (39)		The human mind (39)	39
2. Outcomes					
	a) Emergent			Educational reform (20, 29)	20, 29
	a) Absence of…		"it is impossible to characterize the system on the whole as having a unified purpose" (3) Because… goals in complex systems are variables, not end states (2)		2, 3
B. Reasoning about Systems					
1. Bounded Rationality		Require: Ability to identify and delineate boundaries (23)			23
2. Modes of Behavior					
	a) Central/Decentralized	Novice and expert use different ontologies			10

	(a.k.a. Direct/Emergent)	when constructing solutions to CS problems: Experts solved these problems using a set of "complex systems" onotological statements in which system control as part of decentralized interactions of elements or that described nonlinearities and randomness in action effects in a complex system (20, 21 found in 10) ** see high-school entry for comparison			
	b) Stability/Instability (5)			flow of liquid through pipe (5)	5
	c) Bifurcation - the potential for system variables to jump suddenly from one attractor to another (3)				3
	d) Learning and memory; adaptability – "intelligent" agents (3, 5)			driver or trader (5)	3, 5
	e) Self organization - internal structure changes to conform to/better interact with environment (3)		*Tierra* – model of neo-Darwinian evolution (28)	Neo-Darwinian evolution (28)	3, 28
	f) Dissipation - outside or internal forces drive system into highly unorganized state before it suddenly crossing into one with more organization – Schieve & Allen, 1982 (3)			Economies (external forces, e.g., technology in industrial revolution causes change in structure of economy) (3) Holling (1978, 1995) Ecosystems - fire or pest infestation as cause; redistribution of resources and connectivity as a result (3)	3
	g) Self-organized criticality – ability to balance between randomness and stasis; the system is never organized, but always constantly adapting to prevent collapse – Bak & Chen, 1991; Scheinkman & Woodford, 1994 (3)			Ecological and biogeophysical systems (e.g., Andrde Jr. et al, 1995; Correig et al, 1997) (3)	3

	Irreducibility (5) – combines the concept of emergence and relationships	A complex system is irreducible *because* of its emergent relationships		protein folding (5)	5
C. Modeling Systems/Metacognition/Pedagogy					
	a) Cross-disciplinary	Require: Ability to extend beyond one's own data to hypothesize about other systems (23)			23
	b) Representations	Require: Ability to use imagery and analogies (23)			23
	c) Metaphors				
	d) Modeling	*Algorithmic complexity (3, 26)* • monotonically increasing function of disorder (26) Require: Ability to construct conceptual, empirical and mathematical models (23)	*TRANSIMS* (28)	Mathematical complexity theory (3) Information theory, e.g., classifying remotely sensed imagery, considering the role of ecological community structure on biodiversity (3) *TRANSIMS* – aims to model flow of traffic; inputs include living areas, work, demographics (28)	3, 23, 28
		Phenomena-based modeling (20) • backwards modeling; design strategies to achieve a particular goal	StarPeople (20)		20
		Exploratory modeling (20) • forwards modeling; input rules for individual parts of the system and observe the outcome			20

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