Assessing Students' Development of a System Worldview and System Thinking Skills Using Qualitative Modeling Software

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Abstract

The ability to understand complexity concepts and the behavior of dynamic systems is regarded today as one of the key literacies in the knowledge era. Developing pedagogies aimed to support the learning of these concepts and instruments to assess this learning, is an important educational challenge. This paper describes evaluation studies conducted within an EC funded (7th program) research project that aimed to develop a sophisticated computer tool that enables learners to "dive into complexity", by modeling complex phenomena in the natural, social or artificial world. The evaluation studies that followed this project aimed to assess the effect of learning by modeling using the developed software on understanding complexity and on the development of system perspectives and systems' thinking skills. We will describe these studies, their context, data collection instruments, and criteria used for assessing the understanding and system thinking perspectives and provide findings that support their construct validity.

System Perspective – A New Paradigm for Understanding Complexity

Understanding the structural and behavioral aspects of complex systems has become a challenging intellectual endeavor for scientists and science students (Jacobson & Wilensky, 2006). The development of systemic approaches in the early years of the 20th century marked a shift in perspective that enabled scientists to study phenomena in the world, focusing on aspects, interrelationships and processes that were overlooked by traditional science. The deterministic Newtonian view of the universe as a machine ruled by linear cause and effect gave way to a view of the world that focused on non-linearity, complex webs of causal relationships, and the probabilistic nature of complex phenomena. The Aristotelian dictum that the whole is more than the sum of its parts, ignored in the approaches and philosophical stance of classical science, regained its explanatory power in the foundational principles of theories focusing on the scientific exploration of "wholes" and "wholeness" (von Bertalanffy, 1972; Simon, 1996).

From the educational perspective, the "acculturation" of these novel approaches, methods and tools into educational practice is not trivial. On the conceptual level, the overall systems approach, as well as specific concepts embedded in it (e.g., emergence, self-organization, non-linearity, feedback loops), imply a new way of thinking and represent a serious learning challenge for many students. Some of this knowledge and thinking may appear epistemologically counterintuitive and/or incongruent with the approaches, assumptions and practices that characterize the way students learn science through the curricula prevalent in educational systems. Hence the demand to develop appropriate pedagogical approaches and learning environments for supporting the growth of a system's worldview and the acquisition of system thinking skills.

Two such pedagogical approaches are often in use in learning about complex systems. The first – concept mapping – was developed in the 70s and focuses on diagrammatical representation of systems' ingredients and their interrelationships. A more recent approach advocates Learning by Modeling (LbM) as a promising pedagogical approach for supporting student learning of complex systems (Bredeweg & Forbus, 2003; Hmelo-Silver, Holton, & Kolodner, 2000; Levy & Wilensky, 2008; Svoboda & Passmore, 2011). In line with this approach and borrowing ideas from Qualitative Process Theory (Forbus, 1984), a computer tool for qualitative modeling – DynaLearn – was developed (Bredeweg et al., 2010). This tool allowed the building of qualitative models (i.e., models that provide a conceptual account of a system without assigning numerical or quantitative information to their ingredients), and run simulations to test and understand patterns in systems' behavior.

As part of the development process of DynaLearn, several evaluation studies aimed to trace the development of systems worldview and system thinking skills were conducted. In these studies the two pedagogical approaches were used. Students were asked to represent complex ecological systems by both drawing concept maps and by constructing and manipulating qualitative models using the developed software – DynaLearn. These two pedagogical approaches also served for assessment purposes.

In the present paper we will focus specifically on data from two studies conducted with Junior-high school students. We will describe the constructs assessed, the data collection instruments, and the evaluation criteria used for analyzing the learning products of both the concept mapping and modeling activity. Findings from these studies will demonstrate the growth of system thinking capabilities. Complete reports of these studies appear in the Dynalearn project deliverables (see http://hcs.science.uva.nl/ projects/DynaLearn/).

The Evaluation Studies – Context

The evaluation studies were exploratory in nature. Throughout these studies, students were introduced to several ecological complex systems and were asked to represent these systems in concept maps and to construct and manipulate conceptual models using the developed modeling software – "DynaLearn". Students' mental models and their systems worldview were revealed by analyzing the products of these activities. Comparing the initial concept maps (indicative of students' intuitive mental models) with later products of the modelling process, enabled to trace the growth of system thinking and complexity understanding.

The first study was conducted in the context of a summer course in Marine Biology. Participants were 25 junior high school students (13-14 years old) taking a summer course in an enrichment program initiated by the "Young Persons Institute for Promotion of Creativity and Excellence" at Tel Aviv University. An experimental group of 10 students performed all course activities (field trips, laboratory, lectures and modeling work with DynaLearn). Fifteen students served as a control group who performed all activities, except modeling with DynaLearn, which was replaced by a computer-based inquiry task.

The second study was conducted as part of a 10-hour intervention in a junior high biology class in a comprehensive high school at a kibbutz in the central part of Israel. Students were studying ecological systems before the intervention took place. In the intervention itself, they were introduced to the idea of learning by modeling and used DynaLearn software for modeling in increasing levels of complexity of an ecological river system nearby. The modeling tasks were based on a text describing a phenomenon in the ecosystem (pollution affecting the river ecosystem). Students were asked to follow the text and to represent the system in a concept map and later on to build qualitative models and run simulations that represent the dynamics of the relevant ecological system.

The specific questions addressed in these studies were:

- Does concept mapping and learning by modeling using DyanLearn affect students' understanding of the structural and behavior aspects of complex systems?
- How does students' understanding of the structural and behavioral aspects of complex systems get expressed in their concept maps and qualitative models?

The Evaluation Studies – Design and Evaluation Criteria

All evaluation studies followed a "one group repeated-measures" design (Creswell, 2003), as shown in Figure 1. In it "X" represents the exposure to a sequence of activities: concept mapping or of modeling tasks and 'O' represents an observation or measurement of student performances obtained by different instruments.

O	→	**X**	→	**O**
Observations		Progressions of Concept Mapping (CM) and Modeling (M) Tasks CM_1, CM_2, M_1, M_2		Observations

Figure 1: The Study's Design

The development of system perspectives and systems' thinking skills was assessed through analyses of students' initial, intermediate and final products, using the same evaluation criteria for both concept maps and models. The criteria and scoring guides for assessing systems' worldview and system thinking skills targeted characteristics that refer to both the static and dynamic aspects of systems: structural configuration of entities, quantities used to describe entities and processes, and types of causal configuration and interrelationships in the system. We will detail these criteria in the results section.

Results of the first study

The evaluation study was conducted during a summer course in Marine Biology with two groups of junior high school students: an experimental group exposed to both concept mapping activities and modelling activities and a control group not involved in modelling with DynaLearn software.

Five criteria were used to analyze students' products concerning:

1. The **structural configuration** of the concept map, whether it is of:
   - Hierarchical type (H followed by a number that relates to hierarchical levels)
   - Net-web type (N)
2. **Focus** on the "structural" configuration (S or s depending on the intensity) or focus on representing "processes" (P or p depending on their intensity).
3. **Type of relationship** between entities of the ecosystem in the concept map.
   - Mostly inclusive R1
   - Mostly indicating causal or process relationships R2
   - Both inclusive and causal processes R3
4. The **organizing principle** used to arrange the components of the map:
   - Biological, systematic classification of living organisms (Sys)
   - Ecological principle that relates to the relationship between the living organisms themselves and the non-living elements in their habitat (E).
5. Level of **scientific accuracy** of the representation.
   - High scientific accuracy (Ac3), medium (Ac2), or low (Ac1).

A net or web type of configuration, which focuses both on structural and process elements guided by ecological principles, representing causal relationships or mixed type of relationship – inclusive (structural) and causal (process-oriented) relationships, also demonstrating high level of scientific accuracy was regarded as a favorable response that demonstrates high level of complexity understanding.

Using these criteria two comparisons were made. The first compared initial concept maps of the experimental group with those drawn after students completed the modelling activity, and the second compared post concept maps of the experimental group with these of the control group at the end of the activities. This provided insight into the worth of learning by modelling for achieving system perspective and thinking skills.

Table 1: Analyses of Concept Maps Drawn by the Experimental Group

Student Id.	Structure		Focus On		Organizing Principle		Relationship		Scientific Accuracy (Ac)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	H2		sp		E		R3(2/4)		Ac3	
2	H2		S		E		R1(6/0)		Ac3	
3	H2	N	sp	sp	Sys	E	R3(3/3)	R3(5/5)	Ac3	Ac3
4	N	N	P	P	E	E	R3(8/10)	R3(6/10)	Ac3	Ac3
5	H3	H2	S	Sp	Sys	E	R1(7/0)	R1(5/2)	Ac1	Ac2
6	H3	N	sp	sp	E	E	R3(7/5)	R3(4/4)	Ac3	Ac3
7	N	N	sP	Ps	E	E	R3(16/12)	R3(10/7)	Ac3	Ac3
8	N	H	sP	sp	E	E	R3(9/12)	R3(5/2)	Ac2	Ac3
9	N	N	sP	sp	Sys	Sys	R3(10/7)	R1(10/3)	Ac3	Ac2
10	H		sp		Sys		R1(14/3)		Ac3	

Table 2: Analyses of Concept Maps Drawn by Students in the Control Group - Late Stage

Student Id.	Structure	Focus	Organizing Principle	Relationship	Scientific Accuracy (Ac)
1	H	S	E	R1(5/0)	Ac1
2	H	sp	?	R 3(5/3)	Ac2
3	H	?	?	R 1(5/2)	Ac1
4	H2	sp	E	R 1(9/3)	Ac3
5	H3	S	E	R 3(4/4)	Ac3
6	H2	S	Sys	R 1(10/0)	Ac1
7	H3	Sp	Sys	R 1(5/2)	Ac2
8	H2	s	Sys	R 1(4/0)	Ac1
9	H2	Sp	E	R 3(4/3)	Ac1
10	H3	Sp	E	R 1(1/0)	Ac1
11	H1	Sp	E	R 3(3/2)	Ac1
12	H3	Sp	E	R 1(5/2)	Ac1
13	H2	Sp	Sys	R 3(3/2)	Ac3

Table 3: Comparing the Analyses of Student Concept Map Representation

	Pre-post Experimental Group		Post-post Experimental Control Group
	Pre	Post	Post
Configuration	H= 6/10 = 60% N = 4/10 = 40%	2/7 = 29% 5/7 = 71%	13/13 = 100% 0/13 = 0%
Organizing principle	Sy = 4/10 = 40% E = 6/10 = 60%	1/7 = 14% 6/7 = 86%	4/13 = 31% 7/13 = 54%
Type of relationship	R1 = 3/10 = 30% R2 = 0/10 = 0% R3 = 6/10 = 60%	2/7 = 29% 0/7 = 0% 5/7 = 71%	8/13 = 62% 0/13 = 0% 5/13 = 38%
Scientific accuracy	Ac1 = 1/10 = 10% Ac2 = 1/10 = 10% Ac3 = 8/10 = 80%	0/7 = 0% 2/7 = 29% 5/7 = 71%	8/13 = 62% 2/13 = 15% 3/13 = 23%

Key:
H = Hierarchical configuration; N = Net configuration; S = Organizing principle – Systematic; E = Organizing principle – Ecological; R1 = mostly inclusive relationship; R2 = mostly process relationship; R3 = Mixed relationship; Ac1 = Low level of scientific accuracy; Ac2 = Medium level of scientific accuracy; Ac3 = High level of accuracy

Ten concept maps were produced by the participants of the experimental group at the beginning of the course (pre-concept maps), and seven at the end (post-concept maps). Thirteen concept maps were drawn by the participants of the control group at the end of the activity (post-concept maps). The results are presented in Tables 1, 2, and3.

A synthesis of the data from the three Tables indicates:

1. Concerning Pre- Post- changes in the experimental group's concept maps the trends observed were:
   a) Increase (40% $\rightarrow$ 71%) in Net-type, and decrease (60% $\rightarrow$ 29%) in hierarchical types of representations
   b) Increase (60% $\rightarrow$ 86%) in the use of ecological organizing principles and decrease (40% $\rightarrow$ 14%) in using formal-classification organizing principles
   c) Increase in representing mixed inclusive/process relationships (60% $\rightarrow$ 71%)
   d) Slight decrease in scientific accuracy (80% $\rightarrow$ 70%)

2. Concerning the comparison between the Experimental (E) and Control (C) groups' post-Concept Maps the following trends were observed:
   a) None of the representations in the Control group was Net-like
   b) Less use of ecological organizing principles in the control group (E-86%; C-54%)
   c) Most representations in the C group were structural (inclusive) type (E-29%; C-62%)
   d) Less representations in the C group combined mixed inclusive process relationships (E-79%; C-38%)
   e) Less scientific accuracy in C group's representations (E-71%; C-23%)

In addition to the analyses of the concept maps produced, another analysis was carried out on the products of four consecutive modelling tasks in which students were asked to model different ecological phenomena and to provide a written protocol referring to questions such as: What was the phenomenon represented in the model? Which entities were chosen to represent the phenomenon? and why? Or which properties of the entities were chosen to be quantified?

Analysing the protocols provided additional insights about students' system thinking. For example, Table 4 presents the changes in students' modelling concerning the type of quantities and the patterns of relationships among entities defined in their models. Types of relationships include patterns such as: Unidirectional single or parallel relationship (e.g., "*Wind affects the attachment of the patella to the rock*"); "many-to-one" (e.g., "*Death rate and birth rate affects pop sizes that affects food consumption*"); "chain-of-interactions" (e.g., "*The wind affects the power of the waves that affects the attachment of the patella*"); or "feedback-loops" (e.g., "*The more predators, the less prey; the less prey, the less predators*").

In summing up Table 4, the following changes were observed:

- Student preferred quantity scales that represent amounts and not rates. At the final modelling activity they used notion of rates in only two cases (25%).
- A move from single to parallel unidirectional relationship and a move from parallel toward chain or one to many types of relationships was observed in three cases.
- No change in using a chain type of relationship appearing in 5 out of 9 cases.

Table 4: Types of Quantities Scales and Patterns of Relationships Employed in the First and Last Modelling Attempts

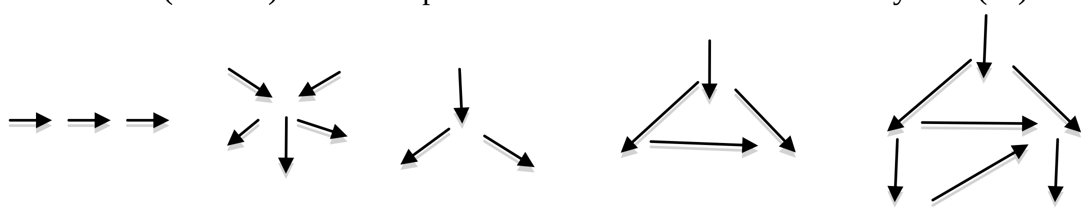
Student ID	Type of Quantity Amount/Rate		Type of Relationship Pattern	
	First	Last	First	Last
1	amount	rate	A→B	A→B B→C
2	amount		A→B→C	-
3	amount	amount	A→B B→C	A→B→C
4	amount	rate	A→B B→C	- A→B→C→D
5	amount	amount	A→B→C	A→B→C→D
6	amount	amount	A→B→C	A→B B→C
7	amount	amount	A→B B→C	A ↘ C→ D ↗ B
8	amount	amount	A→B→C	A→B→C→D
9	amount	amount	-	A→B
10	amount	amount	A→B→C	A→B

Results of the second study

In the second study more attention was given to students perceptions of the dynamic aspects of systems. The criteria used to assess students' system thinking included the following:

a) Students' ways of representing the configuration of the system (see below)

i. "Linear chain" of entities and processes affecting each other (L)
ii. "Sun representation " of elements in a system all related to a central one (S)
iii. "Hierarchical representation" that take into account different levels of inclusiveness in an ecosystem (H)
iv. "Hierarchical with within-levels links" usually referring to complex processes
v. "Weblike" (net like) relationships within and between levels in the system (W).



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b) Indication of the proportion of structural –inclusive versus causal– relationships represented in the system. Here the number of links between entities that describe inclusive relationships versus those that refer to causal processes have been examined.

c) Indication of quantities. The models were examined as to whether the students ignore quantities of in the system's model (0) refer to quantities (Q); refer to quantities and define the direction of the causal relationship between them (Q±).

d) The organizing principle used in the construction of the representation both in the concept maps and in the models. We examined whether the student follows a story and gives a description of an event (E) or s/he organizes the representation around meaningful concepts (C).

The result of analysing both models and concept maps using the same criteria and scoring guides are presented in Table 5.

The analysis of students' modelling capability criteria revealed the following:

a) Concerning the overall configuration of the models, students' represented the phenomena using mainly linear and hierarchical representations. For four out of the fifteen students, a move from linear to hierarchical, or from hierarchical to web-like representations has been observed.

b) Only few of the relationships defined were structural. Most of them described process or causal relationships reflecting the dynamic aspects of the system. Proportions between structural versus process relationship for the CM were: 22% structural and 78% process in the first modelling activity (M1), 17% and 83% correspondingly in the second modelling activity (M2). Almost 100% of the relationships were of the process type. These results indicate that as students gained more experience in modelling they were able to focus more on dynamics aspects – the processes characterizing the interrelationships among the systems' components.

Table 5: Students Modelling Performance*

ID	Configuration			Proportion of structural-to-process links			Quantities		Organizing Principles		
	Cm	M1	M2	Cm	M1	M2	M1	M2	Cm	M1	M2
2	L (8)	L 8	-	0/5	0/5	–	(0)	(0)	E	E	–
6	S8	S8	-	0/7	1/6	—	(0)	(0)	E	E	–
7	H(3)	H(2)	L3 (loop)	3/2	2/2	0/3	(0)	(Q)	C	C	C
9	H(1)	W	W	–	2/6	0/8	(Q)	(Q)	C	C	C
10	L(6)	H(2)	W	0/5	0/7	0/11	(0)	(Q)	E	E	C
12	L(6)	H(2)	L(3)	0/5	0/7	0/2	(0)	(Q±)	E	E	C
15	L(3)	H(2)	L(3) Loop	0/2	2/2	0/3	–	(Q)	E	–	C
16	H(2)	H(2)	L(3)	2/2	1/3	0/2	(0)	(0)	C	C	C
17	H(5)	H(3)	L(4)	3/6	2/5	0/3	(0)	(Q±)	C	C	C
19	S (6)	S(6)	–	0/6	0/6	–	(0)	–	C	C	–
20	L(9)	L(9)	H(1)	0/8	0/8	1/2	(0)	(0)	E	E	E
21	W	S(11)	S(9)	6/4	5/5	0/9	(Q)	(Q)	C	C	C
23	H(3)	W	H2	0/9	1/9	0/4	(Q)	(Q±)	E	E	C
25	W	H(3)	L(5)	8/11	0/7	0/10	(Q)	(Q±)	C	C	C
26	H(3)	H(4)	H(2)	0/5	2/9	0/4	(Q)	(Q±)	C	E	C

(*) Same criteria applied for analysing student Concept Maps (CM), Models 1 and 2 (M1, M2)

c) In all concept maps and in the early models of the river habitat, most students ignored the definition of quantities. However, in their second modelling activity about a new ecological system, ten out of fourteen models included representation of quantities, in half of which they indicated the direction of the relationship between the quantities (marked by '+' or '-'). Repeated experience in modelling seems to support deeper analyses of a phenomenon and refinement in the way of representing its essential traits (e.g., quantities and relationships).Models were also analysed in terms of the organizing principle leading the construction of the model, whether it follows a "story" in correspondence with the text description, or is being built around key concepts distilled from the text description. In the first and second modelling activity (CM and M1), the use of both approaches was evenly distributed. In M2 however, all but one of the models were constructed around concepts. This implies an important change in perspective indicating the development of a deeper and generic systemic approach towards modelled phenomena.
d) Concerning the models' representational structure, students' progress from a linear representation to hierarchical and web-like representation was rare.

Conclusions

In this paper we have described two evaluation studies that followed the development of software that enables learning about complex systems. The studies aimed to evaluate the contribution of using the software to students’ understanding of the structure and behavior of complex systems and their development of a systems' worldview and systems' thinking skills.

The evaluation studies took place in the context of high school students' learning about complex ecological systems. While studying this topic, students were asked to represent complex ecological systems using concept mapping and later to construct qualitative computerized models and run them to explore the dynamic aspects of the systems.

These two activities served, simultaneously both pedagogical and evaluation aims. However, one should take into consideration that as the purpose of the two activities is different revealing different aspects of systems' thinking. While the purpose of concept mapping is to provide a detailed and faithful conceptual account of reality – a descriptive purpose, constructing a model aims to represent a specific case – a segment of reality, to explore its possible behaviors, to choose the most plausible explanations for these behaviors, and to predict it under changing conditions – an explanatory purpose.

These different purposes led indeed to different representations. While concept maps' were found to be more detailed and represented mostly static aspects of a system, models are parsimonious and represent better its dynamic aspects.

We used the same criteria (based on a set of characteristics described in operational terms by Ben-Zvi Assraf & Orion 2005) to analyze both types of products, including students’ narratives for explaining and interpreting the diagrammatic representations. The criteria developed referred to:

- the diagrammatic configuration of the system (i.e., linear, hierarchical or web-like).
- The number of components in the system and type of relationships amongst them (i.e., inclusive or causal)
- Types of quantities employed (i.e, "amounts" or "rates")
- The organizing principles that guided the representation of the system – a structural, conceptual, or temporal event-oriented principle.

Some of these criteria refer to static aspects of a system while others to dynamic ones. Developing and using these criteria required careful observation and analysis of the representations (e.g., graphic patterns, links configuration) as well as of students' explanations and narratives. This guided the impressionistic process used for defining levels of performance. In Table 6 we present the criteria developed for the studies, emphasizing those that relate to dynamic aspects. The table allows to follow the refinement made from the first to the second studies.

An overall summary of he findings through this detailed analysis is shown in Table 7. Summing up, the following conclusion can be drawn: The modeling task performed with the aid of DynaLearn showed clear advances toward a systemic view of complexity. As the modeling task progressed, a move from linear representation of the system structure to a hierarchical one, and then to a web-like configuration, occurred. The modeling activity attracted more attention to causal relationships and to the processes that explain the behavior of the system. It also allows to make a distinction between direct "explicit" causal relationship and hidden indirect relationship that enables to understand the overall emerging behavior of a system. Quantities that were ignored in concept maps were properly addressed in the models. Using measures of "amounts" and "rates of change" allowed to capture dynamic aspects of a system when it adapts to changes in its environment.

Table 6: Criteria Developed in the Context of Two Evaluation Studies

Criteria	First Study	Second Study
Configuration	Hierarchical (with number of levels **Net-Web**	Linear entities affecting each other Sun - all entities related to a central one Hierarchical with levels **Hierarchical with within levels links** **Hierarchical with across levels links**
Relationships	Mostly inclusive **Mostly causal** Mixed inclusive causal	Ratio of inclusive relationship versus processed-causal relationship
Causality patterns	Single or parallel unidirectional **One to many** **Chains** **Feedback loops**	
Quantities/Qualitative Scales	Amounts **Rates of change**	Ignored; **Refer to quantities; Refer to quantities and define direction for the causal relationship**
Organizing Principle	Systematic – inclusive **Ecological-Event-oriented**	Conceptual **Event, story-temporal**
Purpose	Detailed – matching reality Parsimonious – only relevant for a certain question	
Expression of the Modeled Phenomenon	Specific Generic	
Scientific accuracy of the representation	High, medium, Low.	

Table 7: Summary of Findings from the Evaluation Studies

Criteria	First Study	Second Study
1. Configuration	Increase in net-type representations and decrease in hierarchical ones.	About 25% of the students changed their representation from linear to hierarchical or from hierarchical to web-like representation.
2. Relationships	Increase in representing mixed relationships both inclusive and causal	Most of the relationships defined were causal describing processes.
3. Causality	A move from single causal unidirectional relationship to parallel and a further move toward chain or other types	
4. Expressions of quantities	Preference to define quantities on a qualitative scale representing amounts. As the modeling activity progresses, a slight increase in using 'rate of change' (25% of cases).	As the modeling activity progresses, most student define quantities and in half of these cases, they also indicate direction of relationship between quantities.
5. Organizing principle	Preference to organize a system following temporal ecological phenomenon, event or story.	When drawing concept maps half prefer to stick to reality and organize the system around a phenomenon or event. As the modeling activity took place, most students tend to structure the models around cardinal ingredients or concepts.

The findings of this study provided us with a set of evaluation criteria and coding guidelines that allow to distinguish between levels of system thinking in students learning products. More studies with additional data collection instruments, such as observations, recording of think aloud protocols of students' reasoning and decision-making while modeling, are needed for fully detecting students' systems' thinking skills and worldview.

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