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Abstract

Secondary-level students encounter many difficulties in learning complex systems with hierarchical levels. Scaffolding is very critical in teaching complex systems. We have two complementary research questions on scaffolding: 1. How can we chunk and sequence the learning activities in teaching complex systems? 2. How can we help students make connections across system levels? A simulation-based environment teaching a chemical system was used as the research instrument, and the study was conducted at a middle school setting. The results showed that the sequencing method following the "from concrete to abstract" principle produced better recall and comprehension of the system concepts (knowledge integration), while the sequencing method aligned with the casual structure of the system facilitated the construction of a better causal model for transfer. The results also demonstrated that explicit level-bridging scaffolding had positive effects on both knowledge integration and learning the deep causal structure.

Keywords: Complex systems; sequencing methods; level-bridging scaffolding; secondary-level science

Research Background

Complex systems have become an important topic in today's science education. It is usually difficult for students to learn complex systems with hierarchical levels and abstract system dynamics (Jacobson & Wilensky, 2006). Complex systems can be difficult from different perspectives. 1). Spatial-temporal extension of a system, e.g., there are many system levels with complex formation and interactivity 2). Abstract system levels and causal structures in a system, e.g., higher-level patterns emerging from lower-level dynamics (Bar-yam, 1997). Although two types of difficulties always coexist in various complex systems, one may define the complexity more than the other in a specific context or at a certain learning stage. Biological and natural systems often have many system levels, diversified local behaviors and interactivity (Hmelo-silver & Azevedo, 2006). For example, the human circulatory system has a "downward tree" structure with a large number of elements, and varied local element interactivity. Effective knowledge integration is a learning difficulty students have to conquer before learning the emergent processes involved in this type of system. Abstract levels and causal structures are often found in chemical and physics systems (Stieff, 2011). For example, it is difficult to visualize "voltage in an electric circuit" emerging from electrons' behaviors and "gas pressure" from gas molecular activities.

Agent-based modeling and visualizing tools can create visual acuity of system levels and demonstrate cross-level dynamics (Levy & Wilensky, 2009). However, given the complex nature of the learning content, mere perceptual grounding is not sufficient for effective learning. Scaffolding is a critical factor in learning complex systems (Jacobson et al., 2011). The first research question of this study: How can we chunk and sequence the learning activities in teaching complex systems? There have been contradictory findings to this question. However, analyzing the learning difficulties from different perspectives may address the debate over the sequencing methods.

Knowledge integration refers to students connecting scientific concepts and normative ideas, and providing coherent explanations to scientific phenomena (Linn, 2006). From the perspective of knowledge integration, the "top-down" approach starting from the concrete macro-level function of a system is effective. In Liu & Hmelo-Silver (2009)'s study, participants learned the respiratory system with either the "top-down" or the "bottom-up" sequencing method, and the results showed that starting from the system-wide function ("how do we breathe") was better than starting from the lower-level substructures and entities. As can be seen, in this type of biological system, a higher-level function is concrete and easy to understand. And a function is often realized by the interactivity of a large number of diverse lower-level substructures. "Making science accessible" as a knowledge integration guideline informs us that concrete levels of a topic should come before abstract ones (Linn, 2006). Additionally, a top-down function-oriented sequencing method provides a good conceptual structure for knowledge integration (Liu & Hmelo-silver, 2009).

Many studies demonstrate that the "bottom-up" approach is effective in teaching the implicit and abstract causal structure (e.g., emergence) of a complex system (Wilenky & Stroup, 2002). This sequencing method allows students to experience the causal process of how the small effects of the micro-level elements can lead to the macro-level patterns. For example, in the Connected Chemistry Curriculum (Levy & Wilensky, 2009), the approach is to let students manipulate and articulate the micro-level entity behaviors (e.g., how a single gas molecule collide with the walls), and then gradually expand to the emergent processes and phenomena. It is claimed that the "bottom-up" approach help students conceptually understand the implicit linkages between the micro and macro level of the gas phenomena (Levy & Wilensky, 2009).

While we are chunking and sequencing the tasks, we need to provide extra scaffolding for students to make connections across learning activities. Inter-level experience is critical in learning complex systems (Levy & Wilensky, 2009). Thus the second research question of this study is: How can we help students make connections across system levels? Scaffolding that elicits self-explanation could significantly improve learning (Chi et al, 1994). Explicit level-bridging scaffolding such as inter-level questions facilitates self-explanation, and is an effective strategy in teaching complex systems (Stieff, 2011). In this study, the effect of explicit level-bridging scaffolding was tested.

Learning Materials and Instrument

Ideal gas law is a complex chemical system. A concrete phenomenon such as "an aerosol can explodes when it is thrown into the fire" can be defined as the "system-wide" or "pattern-level" function. This level is concrete, observable, and without complex dynamics. Temperature-pressure-volume relationship is an abstract macro level, which is analogous to and explains the observable pattern-level function, thus we define this level as the "mechanism level." This level depicts the mechanism of the "can explosion phenomenon"; meanwhile, this level emerges from the lower-level molecular activity defined as the "entity level".

A simulation-based environment with two simulations was used as the research instrument. The first simulation visualized the pattern-level function. Students could drag the fire icon towards the can and observe the can explodes (see Figure 1). The second simulation (see Figure 2) visualized the mechanism level (Temperature-pressure-volume relationship) and the entity level (molecular activity). The two simulations could be displayed separately on two pages. Students could switch to either simulation by clicking an arrow button, or they could be displayed on the same page and dynamically linked (see Figure 3). The dynamic link technique can facilitate information integration from multiple representations (van der Meji & de Jong, 2006), and in this study, it was a part of the manipulation of the explicit level-bridging scaffolding condition.

Figure 1: Aerosol can simulation

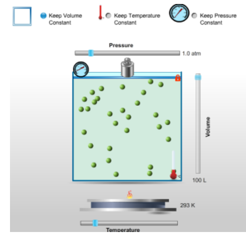

Figure 2: Gas container simulation

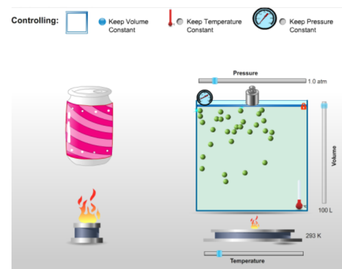

Figure 3: Two simulations dynamically linked

Variables & Hypotheses

Two variables were tested in this study: 1. Sequencing methods; 2. Level-bridging scaffolding.

Sequencing Methods

Three sequencing methods were compared in this study. The sequencing methods variable was manipulated by changing the delivery order of the three levels of the chemical system.

F-M-E sequencing method Starting from the function level to the mechanism level, and then to the entity level (F-M-E). This sequencing method followed the "from concrete to abstract" principle. It was function-oriented thus provided a good conceptual framework for knowledge integration.

E-M-F sequencing method Starting from the entity level to the mechanism level, and then to the function level (E-M-F). This sequencing method followed the "from cause to effect" principle because it was aligned with the causal structure of the ideal gas law system

M-E-F sequencing method Starting from the mechanism level to the entity level, and then to the function level (M-E-F). This sequencing method did not follow the "from concrete to abstract" or the "from cause to effect" principle, thus it was hypothesized to be less effective than the other two methods.

Hypotheses on Sequencing Methods

Hypothesis 1 the F-M-E sequencing method produces better knowledge integration when compared to the E-M-F and the M-E-F sequencing method.

Hypothesis 2 the E-M-F sequencing method produces better understanding of the deep causal structure when compared to the F-M-E and the M-E-F sequencing method.

Hypotheses on Level-Bridging Scaffolding

Explicit level-bridging scaffolding and implicit level-bridging scaffolding were compared in this study.

Hypothesis 3 Explicit level-bridging scaffolding produces better knowledge integration when compared to implicit level-bridging scaffolding

Hypothesis 4 Explicit level-bridging scaffolding produces better understanding of the deep causal structure when compared to implicit level-bridging scaffolding.

Method

Participants

129 seventh graders from two inner city public middle schools participated in this study. Six cases were dropped from the sample, as these participants were absent from the second session of the study. The final sample included 123 participants. 78.9% were Hispanic, 13.8% Black, 4.1% white and 3.3% other. The mean age of this sample was 12.4 (SD=0.53). 48.8% were male and 51.2% female.

This study employed a 3x2 design. See Table 1 for the 6 treatment groups.

Table 1: 3x2 experimental design

	F-M-E	E-M-F	M-E-F
Explicit level bridging	Group 1	Group 3	Group 5
Implicit level bridging	Group 2	Group 4	Group 6

Procedure

Within each classroom, participants were randomly assigned. The data collection within each class was operated on two consecutive days. The total length of the two sessions was around 100 minutes.

Day 1 All participants took a pretest. Within the same classroom, participants were randomly paired up and randomly assigned to a condition. Each pair was assigned a laptop with the simulations; and each participant was assigned a booklet with 6 learning activities. Participants were asked to read the guidance and questions on the worksheets and write down their answers without any group discussion (for better control of extraneous factors). Three research assistants and the science teacher were present to monitor the learning progress, help change the simulation interfaces and solve technical problems. Participants completed 3-4 learning activities on Day 1.

Day 2 Participants were assigned to the same group as Day 1. They were asked to spend around 5 minutes reviewing their work from Day 1. Participants continued learning and completed the rest of the learning activities. Participants completed a posttest after the learning session.

Manipulation

Sequencing Methods Sequencing methods were manipulated by changing the delivery order of these three system levels. The same learning activities on three system levels were arranged in different orders.

Level-Bridging Scaffolding This variable was manipulated on two aspects. For the explicit level-bridging condition: 1). Inserting inter-level questions among the learning activities 2). Two simulations were dynamically linked for the final learning activity (See Figure 3.). For the implicit level-bridging condition: 1). Inserting intra-level questions among the learning activities 2). Two simulations were not dynamically linked for the final learning activity.

The inter-level questions and intra-level questions were manipulated in a way that the same amount of information was delivered. Please see Table 2 for the two sets of questions. Where each question was inserted also depended on the sequencing method condition.

Table 2: Inter-level questions vs. Intra-level questions

<table>
<tr><th>Inter-level questions</th><th>Intra-level questions</th></tr>
<tr><td>1. What is the relationship between temperature and pressure? Use what you learned about temperature and pressure from the gas container presentation, explain why the aerosol can explodes?</td><td rowspan="3">1.Explain why the aerosol can explodes?

2. Use what you learned about temperature and pressure from the gas container presentation, explain what is the relationship between temperature and pressure?

3. Use the knowledge of gas molecules; explain how do gas molecules behave?

4.Explain what happens to the aerosol can as you drag the fire closer?

5.What did you learn from the aerosol can presentation?

6.As temperature rises, pressure also rises, is this correct?

7.What did you learn about gas molecules?</td></tr>
<tr><td>2. How do gas molecules behave? Use what you learned about gas molecules; explain why as temperature rises, pressure inside the container also rises?</td></tr>
<tr><td>3. Use the knowledge of gas molecules; explain what happens to the gas pressure inside the aerosol can as you drag the fire closer? Explain why the aerosol can explodes?</td></tr>
</table>

Measures

Pretest The pretest included two open-ended questions asking the participants to explain two ideal gas law problems: “using an ice pack to reduce tooth pain” and “car tires are more likely to explode in the summer than in the winter”. No extra system information about ideal gas law was provided, as priming the participants with any level of the system might disrupt the manipulation of the sequencing methods.

Posttest. The posttest included four parts. Part I. short answer questions and labeling questions measuring recall of system knowledge. Part II. Two snapshots of the virtual experiment simulation were provided, participants were asked to describe what happened from Time A to time B. This open-ended question measured recall of simulation events; Part III. Four open-ended questions measured comprehension of the system knowledge, e.g., participants were asked to explain their understanding of “gas pressure”, and “why the aerosol can explodes”. Part IV. The same two ideal gas law problems as in the pretest were used as transfer questions. This part measured understanding of the deep causal structure of the system.

Most of the questions in the pre and posttest were open-ended questions. Participants’ answers were coded on the absence or presence of important system knowledge units. All possible knowledge units were included in the coding scheme (possible maximum scores were high), but participants’ actual scores were relatively low.

Two raters blind to the conditions coded the answers independently, and the inter-rater reliability was above 95% for all parts of the pre and posttest. Disagreement was resolved via discussion between the two raters.

Results

Pretest Scores

The possible maximum score of the pretest was 10. Pretest scores did not significantly differ across sequencing methods, $F(2, 117)=0.674$, $p=0,512$; or across level-bridging scaffolding conditions, $F(1, 117)=0.238$, $p=0.789$. The pretest scores were used to establish equivalency and used as a covariate in further analysis.

Table 3. Pretest scores

	F-M-E	E-M-F	M-E-F	Marginal
Explicit Level-bridging	1.33 SD=0.65 N=20	M=1.45 SD=1.08 N=19	M=1.16 SD=0.90 N=22	M=1.30 SD=0.89 N=30
Implicit level-bridging	M=1.20 SD=0.88 N=20	M=1.46 SD=1.05 N=23	M=1.32 SD=0.85 N=19	M=1.33 SD=0.93 N=62
Marginal	M=1.26 SD=0.77 N=40	M=1.45 SD=1.05 N=42	M=1.23 SD=0.87 N=41	Total M=1.10 SD=0.65 N=123

Posttest Scores

Knowledge integration was measured through recall and comprehension tasks (Part I, II, III), and understanding of the deep causal structure was measured through transfer tasks (Part IV). ANCOVA and helmert contrasts were conducted as inferential tests.

Part I. Recall of system knowledge (possible maximum score= 8) Two statistical outliers were converted to the 98-percentile value of the sample distribution. Descriptive data of this part please see Table 4 and Figure 4. Pretest scores as a covariate was marginally significant, $F(1, 116)=3.36$, $p=0.069$. No interaction between sequencing methods and level-bridging scaffolding was found, $F(2, 116)=0.212$, $p=0.847$, indicating the F-M-E sequencing method and explicit level-bridging scaffolding had additive effects on the recall of system knowledge. The Helmert contrasts results showed that the F-M-E sequencing method produced significantly better recall when compared to the average of the other two sequencing methods, $t(116)=2.56$, $p=0.012$; no significant difference was found between the E-M-F and the M-E-F sequencing method, $t(116)=0.13$, $p=0.894$. This demonstrated that the “top-down” function-oriented sequencing method following the “concrete to abstract” principle (F-M-E) provided a desirable conceptual framework for knowledge integration. Explicit level-bridging scaffolding had significant positive effects on the recall of system knowledge, $F(1, 116)=7.24$, $p=0.008$. The results supported Hypothesis 1 and 3.

Table 4. Recall of system knowledge

	F-M-E	E-M-F	M-E-F	Marginal
Explicit Level-bridging	M=4.30 SD=1.08 N=20	M=3.45 SD=1.19 N=19	M=3.50 SD=1.53 N=22	M=3.77 SD=1.26 N=61
Implicit level-bridging	M=3.45 SD=1.19 N=20	M=3.00 SD=1.65 N=23	M=3.00 SD=1.20 N=19	M=3.14 SD=1.37 N=62
Marginal	M=3.88 SD=1.20 N=40	M=3.24 SD=1.38 N=42	M=3.27 SD=1.40 N=41	Total M=3.46 SD=1.35 N=123

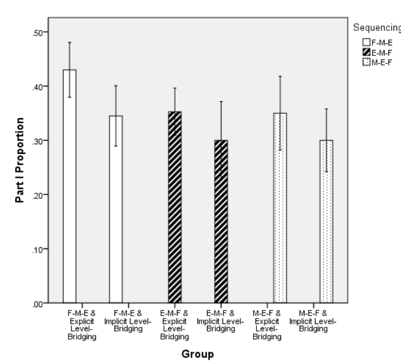

Figure 4. Recall of system knowledge

Part II. Recall of simulation events (possible maximum score=6) One statistical outlier was converted to the 99-percentile value of this sample. Descriptive data of this part please see Table 5 and Figure 5. Pretest scores as a covariate was not significant, F(1, 116)=1.11, p=0.29. The F-M-E & Implicit level-bridging group recalled more simulation events when compared to the other treatment groups. As statistical evidence for that, the interaction between the sequencing methods contrast (F-M-E vs. other) and the level-bridging scaffolding variable was significant, t(116)=2.03, p=0.045, meaning that the F-M-E was effective on the recall of simulation events only in the implicit level-bridging condition. The results from Part I and II indicated that the F-M-E sequencing method led to better recall in general. Given explicit level-bridging scaffolding, students were more likely to integrate important system concepts; while in the implicit level-bridging scaffolding condition, participants focused more on superficial simulation events.

Table 5. Recall of simulation events

	F-M-E	E-M-F	M-E-F	Marginal
Explicit Level-bridging	M=1.75 SD=0.55 N=20	M=1.79 SD=0.71 N=19	M=1.86 SD=0.83 N=22	M=1.80 SD=0.70 N=61
Implicit level-bridging	M=2.30 SD=0.66 N=20	M=1.83 SD=0.83 N=23	M=1.84 SD=0.60 N=19	M=1.98 SD=0.74 N=62
Marginal	M=2.02 SD=0.66 N=40	M=1.81 SD=0.77 N=42	M=1.85 SD=0.73 N=41	Total M=1.89 SD=0.72 N=123

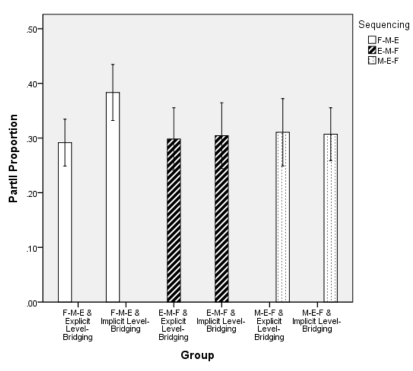

Figure 5: Recall of simulation events

Part III. Comprehension (possible maximum score=15) Descriptive data of this part please see Table 6 and Figure 6. Pretest scores were significantly associated with the comprehension scores, F(1, 116)=8.51, p=.004. The interaction between sequencing methods and level-bridging scaffolding was not significant, F(2, 116)=0.049, p=.952, indicating the effects of sequencing methods and level-bridging scaffolding were additive. Although this part showed a similar pattern as Part I, the positive effects of F-M-E sequencing method over the average of the other two was not significant, t(116)=1.46, p=0.146. Significant main effects of the explicit level-bridging scaffolding was found, F(1, 116)=4.45, p=0.037<0.05. When comparing Part I and Part III, we may find that the effects of explicit level-bridging scaffolding on knowledge integration was more sustainable than the F-M-E sequencing method.

Table 6. Comprehension of system knowledge

	F-M-E	E-M-F	M-E-F	Marginal
Explicit Level-bridging	M=3.97 SD=1.41 N=20	M=3.53 SD=1.57 N=19	M=3.34 SD=2.01 N=22	M=3.60 SD=1.70 N=61
Implicit level-bridging	M=3.20 SD=1.64 N=20	M=2.89 SD=1.27 N=23	M=2.92 SD=1.98 N=19	M=3.30 SD=1.61 N=62
Marginal	M=3.58 SD=1.56 N=40	M=3.18 SD=1.43 N=42	M=3.15 SD=3.15 N=41	Total M=3.30 SD=1.68 N=123

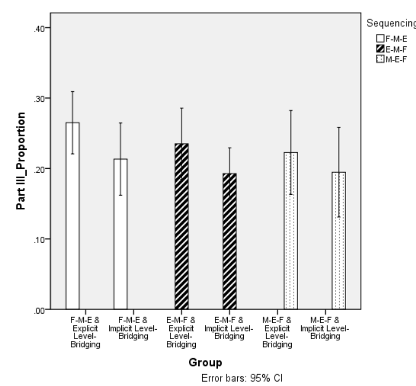

Figure 6: Comprehension of system knowledge

Part IV. Transfer tasks (possible maximum score=10) Different from the comprehension questions in Part III, these two transfer questions required participants to recognize the problems as ideal gas law phenomena, and transfer the causal structure of the system to explain the problems. Two statistical outliers were converted to the 98-percentile value of the sample distribution. Descriptive data of this part please see Table 7 and Figure 7. These two transfer questions were the same as the pretest questions. The mean pre-post gain was 0.68, SD=1.33, which was significantly different from 0, t (122)=5.66, p<.001. However, the low pre-post gain indicated that transfer was inherently difficult.

The E-M-F sequencing method with explicit level-bridging scaffolding was the most effective treatment in teaching the deep causal structure of the system. As statistical evidence for the claim, the interaction of the sequencing methods contrast (E-M-F vs. other) and the explicit level-bridging scaffolding variable was significant, t(116)=2.04, p=0.044. This indicated that a "bottom-up" approach aligned with the causal structure was effective only when explicit level-bridging scaffolding was provided. The results provided evidence to Hypothesis 2 and Hypothesis 4.

Table 7. Transfer_Understanding of the deep causal structure

	F-M-E	E-M-F	M-E-F	Marginal
Explicit Level-bridging	M=1.95 SD=1.15 N=20	M=2.97 SD=1.72 N=19	M=1.80 SD=1.46 N=22	M=2.21 SD=1.34 N=61
Implicit level-bridging	M=1.85 SD=1.55 N=20	M=1.82 SD=1.22 N=23	M=1.63 SD=1.30 N=19	M=1.78 SD=1.34 N=62
Marginal	M=1.90 SD=1.35 N=40	M=2.35 SD=1.56 N=42	M=1.71 SD=1.34 N=41	Total M=2.00 SD=1.45 N=123

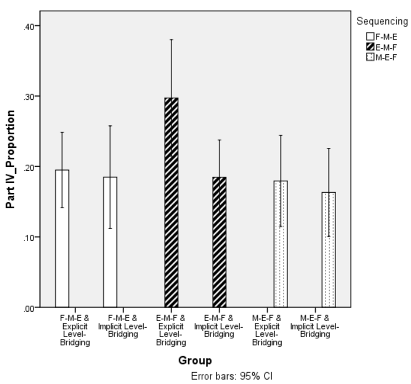

Figure 7: Transfer_Understanding of the deep causal structure

Conclusion

Scaffolding is critical in teaching complex systems. Different sequencing methods as procedural scaffolding were compared in this study. The F-M-E sequencing method which followed the "concrete to abstract" sequencing principle produced better knowledge integration. The E-M-F sequencing method which followed the "cause to effect" principle produced better understanding of the deep causal structure only when explicit level-bridging scaffolding was provided. The M-E-F sequencing which did not follow either principle was not very effective for either knowledge integration or understanding of the deep causal structure. These findings are valuable as they address the "top-down" vs. "bottom-up" debate in teaching complex systems. When teaching systems with many levels and detailed system dynamics, effective knowledge integration is very essential at an early stage, thus the "top-down" approach starting from concrete macro-level functions may produce better performance. While in teaching complex systems with abstract and implicit causal structures, a sequencing method aligned with the causal structure of the system may help learners construct better mental models for transfer. Different sequencing methods can be used in different contexts or at different learning stages.

The results also showed that explicit level-bridging scaffolding had positive effects on both knowledge integration and understanding of the causal structure. From the perspective of knowledge integration, level-bridging scaffolding and the F-M-E sequencing method had additive effects. In learning the deep causal structure, merely delivering the system knowledge in a "bottom-up" approach was not sufficient, and explicit level-bridging scaffolding was necessary in this process. The positive effects of the explicit level-bridging scaffolding are worth emphasizing. We need to explicitly encourage learners to make connections across system levels via inter-level questions and technology-enhanced techniques (e.g. dynamic link of two simulations). Future research is needed to study the separate effects of different level-bridging scaffolding strategies.

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