Improving the Design and Impact of Interactive, Dynamic Visualizations for Science Learning

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Abstract: This interactive poster session features seven research groups exploring how interactive, dynamic visualizations impact student learning. Six empirical studies report on promising designs for visualizations. These studies use logs of student interactions and embedded assessments to document the quality and trajectory of learning and to capture the cognitive and social processes mediated by the visualization. The review synthesizes previous and current empirical work. It offers design guidelines, principles, patterns, and examples to inform those designing interactive, dynamic visualization and aligned learning support. These posters show why dynamic visualizations are both difficult to design and valuable for science instruction.

Introduction

The value of interactive, dynamic visualizations in education is contested. Research on the impact of computer simulations, dynamic visualizations, or animations in science education indicates mixed results (e.g., Tversky, Bauer Morrison, & Betrancourt, 2002). Research shows that success of visualizations in science classrooms depends on many factors, including learners' prior knowledge, experience, or ability (e.g., Hegarty, Kriz, & Cate, 2003), learners' strategies, actions, and interactions with the visualization (e.g., Lowe, 2004), and learning processes guided by the instructional environment (Linn & Eylon, 2006). To take advantage of interactive, dynamic visualizations of complex scientific phenomena students need cognitive guidance and support. In this session we will identify promising principles, patterns, and design criteria for making visualizations effective.

Advances in technology make research on visualization more powerful and informative. It is possible to trace students' responses, actions, and interactions as they learn with visualizations. Logs of student interactions and embedded assessments can reveal the quality and trajectory of learning, and capture the cognitive and social processes mediated by the computer visualization. Researchers can compare alternative forms of instruction to clarify how to make visualizations effective, designing guidance and feedback tailored to the needs of the student. In this session, six groups of designers who developed online learning environments that incorporate the use of interactive, dynamic visualizations will report on how student logs and embedded assessments obtained during classroom trials and other learning settings provide feedback on the effectiveness of their design and suggest revisions for further development. The seventh study reviews literature on the design and assessment of dynamic visualizations and synthesizes effective design strategies and principles. The symposium will initiate a dialogue connecting evidence from previous, current and future studies. It will engage participants in discussing diverse viewpoints concerning how to design interactive, dynamic visualizations and related learning support to benefit student understanding of science in educational and everyday settings.

Rationale

Computer visualizations show promise for helping students understand complex science content. They can bring unseen phenomena to life. They can capture processes occurring over very long and very short time frames (Large, 1996). The increasing capabilities of computer programs and displays broaden the interaction between the learner and visualization. Well-designed interactions can increase the impact and effectiveness of dynamic visualizations (Linn & Eylon, 2006).

Despite the potential benefits of embedding computer visualization in instruction, studies have identified at least five types of student difficulties in learning with visualizations, including attending to the information of the visualization (e.g., Rieber, 1989), conceiving dynamic processes or abstract relationships (e.g., Hegarty et. al., 2003), connecting visualizations to everyday experiences (e.g., Nakhleh, Samarapungavan, & Saglam, 2005), making transformations between multiple representations (Kozma, 2003), and understanding the purpose of using scientific visualizations (Treagust, Chittleborough, & Mamiala, 2002). The posters in this session employ a knowledge-integration design approach (Linn & Eylon, 2006) to address these learning difficulties. Individually and collectively, the posters incorporate aspects of the knowledge-integration approach in the design of instruction featuring interactive, dynamic visualizations and learning supports. These include (1) considering student ideas and difficulties when designing visualizations, learning tasks, and group activities, (2) linking multiple visualizations across contexts to help students develop integrated understanding that connects to everyday experiences, and (3) examining data from student artifacts and actions during the learning process and using this evidence to refine design features and improve learning outcomes. The instructional materials employed in the empirical studies have all undergone classroom trials and refinement before the investigations reported in this symposium were conducted.

Session Structure and Participating Posters

The symposium is planned as an interactive poster session. The session chair, Marcia Linn, will introduce the speakers and the background of the session. Each presenter will then give a two-minute introduction to their research. For the next 40 minutes, attendees can visit each poster and converse with individual presenters. Presenters will have posters and interactive demonstrations of the technologies used in their research. After the viewing, the discussant, Chris Quintana, will comment on the presentations and moderate a discussion that allows presenters and attendees to share their insights.

The empirical studies each explore ways to design interactive, dynamic visualizations and supporting learning activities to help students overcome difficulties in learning complex science and develop integrated understanding. They employ online learning environments and incorporate visualizations using tools such as Molecular Workbench (Xie & Tinker, 2006), NetLogo (Wilensky, 1999), and GeoWall (Morin, 2004). In these learning environments the visualizations are integrated with instructional scaffolding, such as inquiry maps and embedded prompts, and learning activities, such as online discussions and scientific experimentation. The design of the instruction involves both the visualization and related learning support or activities. For example, Figure 1 shows a screenshot of the learning environment reported in Chiu's study. The dynamic molecular visualization is linked with other visual and textual representations and integrated with activity prompts that support effective learning about chemical reactions. Figure 2 shows a screen shot of an interactive, dynamic visualization used in the study by Varma. The learning environment guides students to conduct experiments with the NetLogo visualization to explore the role of several factors involved in the greenhouse effect.

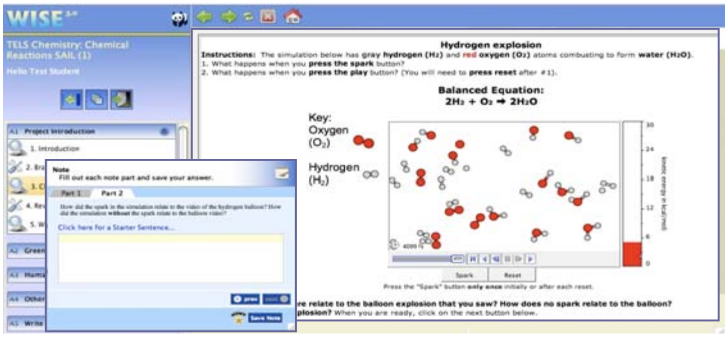

Figure 1. A screenshot of a dynamic molecular visualization supported by activity prompts used in Chiu's study

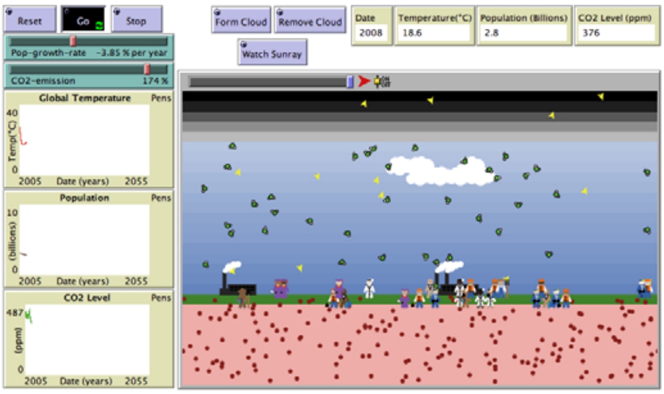

Figure 2. A screenshot of a NetLogo greenhouse visualization used in Varma's study

The methodology for the six empirical studies draws on logs of students' interactions with the visualizations, discussions, and embedded assessments in authentic learning environments such as classrooms or informal educational settings. The studies assess the quality of students' artifacts, actions, and strategies as they learn with visualizations. The results indicate the extent to which a target design feature has impact on student learning and suggest challenging areas for further design and investigation. The seventh poster synthesizes findings from the studies of this session and discusses links among previous, current and future studies. The research focus, design strategy and research outcome for each presentation are summarized in Table 1.

Table 1: Summary of research focus, strategy for designing visualizations and learning support, and research outcome for each presentation.

Presenter	Research Focus	Design Strategy	Research Outcome
Chiu	Investigation of the use of self-monitoring and explanation prompts to help students effectively interact with dynamic simulations of chemical reaction	Vary design and placement of self-monitoring and explanation prompts to help students interpret molecular visualizations	Evidence showing that explanation prompt placement can impact student patterns of interactions with the visualizations
Clark *et al.*	Investigation of how social interactions impact students' interpretations of visualizations of heat and temperature	Compare two levels of scaffolding that vary on the amount of personalization allowed	Evidence of the value for using explicit scaffolds to improve learning from visualizations
McElhaney	Investigation of relationships between experimentation and learning from a dynamic visualization of motion	Examine the impact of connections between experimentation strategies and domain knowledge on learning	Evidence of the role of domain-specific knowledge in learning from experimentation with visualizations
Varma	Investigation of students' experimentation strategies and role of scientific knowledge in using a greenhouse visualization	Compare the patterns of experimentation and role of scaffolds in exploring a greenhouse visualization	Evidence of benefits of visualizations on students' experimentation strategies and content knowledge
Price & Lee	Investigation of students' understanding of science concepts at non-tactile scales	Study 3-D enhanced virtual environment with varied learning tasks	Evidence of interaction between representation type and task demand
Shen	Investigation of supports to help students connect observations of scientific phenomena and atomic level explanations of static electricity	Capture patterns used to link everyday experience to transformations among multiple representations of electricity	Evidence that students' prior knowledge influence their learning from dynamic visualizations
Chang	Review and synthesis of 68 studies of how dynamic visualization could support science learning	Identify five design principles to remedy learning difficulties based on empirical research	Synthesis of effective design strategies, patterns, and principles to guide future designers

Examining the Role of Self-Monitoring and Explanation Prompts on Students' Interactions with Dynamic Molecular Visualizations

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Dynamic molecular visualizations can help students integrate macroscopic, symbolic, and molecular representations of chemical phenomena. For instance, students traditionally have difficulty interpreting chemical equations, such as $2H_2 + O_2 \rightarrow 2H_2O$, as breaking and forming bonds among atoms and molecules (Ben-Zvi, Eylon & Silberstein, 1987). Research demonstrates that dynamic molecular visualizations have the potential to help students connect molecular accounts of chemical phenomena to their symbolic and macroscopic counterparts (Wu, Krajcik, & Soloway, 2001). However, novice learners have difficulty using dynamic visualizations to build coherent mental models of complex phenomena (Lowe, 2004). Students have trouble focusing on relevant aspects of visualizations, monitoring their understanding while interacting with visualizations, and connecting ideas from visualizations to existing ideas. Eliciting explanations can encourage integration of knowledge (Chi, de Leeuw, Chiu & Lavancher, 1994) and prompting self-assessment can support students' development of self-monitoring skills (White & Frederiksen, 1998). Thus, prompting students to explain connections among visualizations and other representations provides support to direct students' attention and can help students develop more integrated views of chemistry. Encouraging self-assessment can help students monitor their understanding while interacting with visualizations.

This study explores how eliciting explanations that connect dynamic molecular visualizations and representations of chemical reactions combined with prompting self-assessments of these connections can influence students' interactions with dynamic molecular visualizations in technology-enhanced curricula. Computational visualizations of chemical reactions from Molecular Workbench (Xie & Tinker, 2006) were embedded within a week-long computer-based inquiry curriculum unit on chemical reactions using the Web-based Inquiry Science Environment (WISE, Linn & Hsi, 2000). Approximately 120 high school chemistry students explored how chemical reactions relate to global climate change using various pedagogical tools of WISE such as discussions, videos, drawing, and journals. Within this larger curriculum, sequenced steps guided students to interact with dynamic molecular visualizations, assess their understanding, and explain connections among visualizations and representations of chemical reactions. Using data logging capabilities of the WISE environment, this study captured when and where students clicked on each step of the entire curriculum. Analysis of these logs focused on describing when students chose to revisit steps out of sequence and common patterns of these instances. Initial results demonstrate the most common revisiting pattern to be from explanation steps to dynamic molecular visualizations. These results suggest that eliciting explanations that connect visualizations to other ideas may help students identify what they do not understand and encourage students to revisit visualizations to remedy gaps in knowledge.

Scaffolding Students' Argumentation about Simulations

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Simulations provide rich representations for students exploring science phenomena. Students often interpret these simulations, however, in non-normative ways. Essentially, novices have difficulty focusing on the appropriate aspects and the appropriate levels of abstraction that seem so transparent for experts (e.g., Brewer & Nakamura, 1984; Schank & Abelson, 1977). Spreading the cognitive load of interpreting visualizations across a larger social group has been suggested by many theorists (e.g., Andriessen, Baker, & Suthers, 2003; Driver, Newton, & Osborne, 2000; Duschl, 2000; Koschmann, 2002). The challenge involves organizing these social interactions to best support students' investigation of the richness afforded by the visualizations.

This study investigates seven classes of high school students investigating thermal equilibrium through a series of experiments and visualizations in an online science learning environment. After conducting their investigations, students use a series of pull-down menus to construct an explanation for the patterns they observe in the data. The interface constrains the aspects of the visualizations upon which they can focus. These students are then assigned by the software to online discussions with students that created explanations different than theirs. Discussion groups are randomly assigned to experimental conditions where either (a) their own interpretations of the simulations become the seed comments in the online discussion, or (b) preselected comments chosen to represent a range of plausible interpretations become the seed comments in the discussion. The results of the study clarify the tradeoffs in terms of the increased personal engagement of the students in the resulting discussions. Discussion also considers how nuances in the implementation of the experimental conditions can impact outcomes.

Connections Between Students' Experimentation Strategies With a Dynamic Visualization and Their Domain Knowledge

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This study examines how students connect experimentation strategies to domain knowledge and how these connections contribute to learning from a dynamic visualization. Physics students (N=148) in six diverse high school classroom settings studied a week-long inquiry module titled *Airbags: Too Fast, Too Furious?* concerning the safety of airbags in car collisions. *Airbags* engages students in making challenging conceptual connections among motion, graphs, and the safety of airbags. New logging technology records students' investigation goals and experimentation sequences as they interact with a dynamic visualization. While some research on experimentation suggests that students' experimentation knowledge is mainly domain general and may be applied in multiple domains (e.g. Klahr & Nigam, 2004), other studies highlight the importance of incorporating domain-specific understanding into experimentation (e.g. Schauble, 1996). The current study extends this work by using the knowledge integration framework (Linn & Eylon, 2006) to measure the quality of students' knowledge connections between domain knowledge and experimentation strategies and linking these connections to learning outcomes.

In *Airbags*, students experiment with a visualization showing an animation and coordinated position and velocity graphs of an airbag and driver. Students specify an investigation question and the values of three variables (position, velocity, and time) that affect the driver's risk for injury from an airbag. Students conduct as many trials as they need to answer the investigation questions. Students' understanding of motion graphs and the safety of airbags is assessed using pretests/posttests and embedded assessments, where students interpret graphs and draw conclusions from their experiments. These are scored using a knowledge integration rubric (Linn, Lee, Tinker, Husic, & Chiu, 2006). Students' experimentation sequences are scored in three ways: the total number of trials students conduct, how well students control variables across trials, and the alignment of students' experimentation strategies with their investigation questions.

Regression models relate these three experimentation scores to learning outcomes controlling for students' prior knowledge. Results show that alignment between students' experimentation strategies and investigation questions strongly and significantly predicted learning, while controlling variables without regard for the investigation question did not significantly predict learning. The findings illustrate the importance of domain specific knowledge and advance planning in learning from experimentation. This research also suggests new ways to use logging technologies to scaffold students' interaction with computer-based visualizations, such as providing appropriate guidance for students who have difficulty conducting valid experiments.

Supporting Students' Experimentation Strategies with Dynamic Visualizations

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Dynamic visualizations can help students learn about complex scientific concepts and phenomena. They can make abstract information more accessible, show relationships between multiple concepts, and allow students to actively learn about scientific ideas via real-time interactions. This study focuses on supporting students' experimentation strategies as they interact with a complex visualization of the greenhouse effect. The research questions are: (1) What content knowledge and experimentation strategies do students learn? (2) What type of scaffolding best supports students to learn effective experimentation strategies?

Even though younger students struggle to design valid experiments, they can learn effective experimentation strategies (e.g., Schauble, 1996). However, there is much debate over what should be the focus of instruction on scientific knowledge and experimentation (e.g., Kuhn & Dean, 2005). In the module, students conduct experiments with the greenhouse visualization by manipulating levels of solar energy, atmospheric carbon dioxide, Albedo, sunlight, and cloud cover. Activities prompt students to make predictions and then plan experiments to test their ideas. Following their investigations, students draw conclusions about the role of the different factors involved in the greenhouse effect. The guided support also directs students to change only one variable at a time as they conduct their experiments, to encourage valid investigations leading to normative scientific ideas (Klahr & Nigam, 2004).

Middle school students (N=137) worked in pairs to participate in the module. Each group completed reflection notes embedded throughout the project. The note prompts helped to guide their experimentation. Students' responses provide evidence of their thinking and experimentation strategies. Each individual student also participated in pre/post assessments of their understanding of the greenhouse effect. Posttest scores about students' understanding of the greenhouse effect were reliably higher than pretest scores. Following their participation in the module, students had fewer misconceptions about the factors involved in the greenhouse effect. Analysis of students' experimentation plans revealed a wide range of strategies with very few students understanding that they should use the control of variables strategy. A follow-up study investigated how to help students learn effective experimentation strategies by providing different levels of support. Data logs were generated to show exactly how students designed and conducted experiments with the greenhouse visualization. This information and data from students' reflections in their embedded notes demonstrate how interactive visualizations combined with experimentation guidance can help students build effective experimentation strategies. These findings suggest principles for design of inquiry learning using dynamic visualizations.

Assessing Spatial Cognition in Stereoscopic Environments

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Students find it challenging to perceive scientific objects at non-tactile scales, those too small, e.g. atoms and molecules, and those too large to see, e.g., galaxy clusters (Tretter, Jones, & Minogue, 2006). Many of these objects often require students to perform three-dimensional manipulations to accurately understand structural properties such as rotational symmetries. However, students typically experience these objects in a two dimensional space as in pictures, diagrams, and photos on printed media. Stereoscopic visualizations can provide students with unique opportunities to manipulate and investigate these objects in their real dimensions. This study investigated how stereoscopic visualizations, as compared to typical 2D visualizations, affect students' ability to perform spatial cognition tasks.

This study included nineteen middle school aged visitors to the Space Visualization Laboratory (SVL) at the Adler Planetarium in Chicago, IL. The researcher randomly selected students for participation. The participants first took a test booklet that included three previously validated spatial tasks: the letter rotation task

(Shah & Miyake, 1996), the paper folding task (Ekstrom, et al. 1976), and the block rotation task (Bodner & Guay, 1997). These three tasks demanded students to use increasingly sophisticated three-dimensional visualization abilities. Next, the students repeated the same sequence of tasks with stereoscopic visualizations shown in the GeoWall environment (Morin, 2004). Two outcome measures were obtained: success rate and completion time on each of the three tasks. We then analyzed student performance data using mixed effects ANOVA's. The independent variables were visualization type (2D vs. stereoscopic) and spatial task (letter vs. paper vs. block). We also conducted post-task interviews with the subjects on how they solved each task and which format they preferred to solve the task and why.

Results show that there was no difference in success rate between 2D (M=1.7, SD=.56) and stereoscopic (M=1.6, SD=.44), $F(1)=1.025$, $p=.32$. There was a significant interaction effect between students and task type, $F(36)=1.97$, $p<.05$, indicating that some students performed consistently better on certain types of tasks. Results also show a statistically significant increase in completion time, $F(1)=11.6$, $p<.01$, going from the 2D (M=320 seconds, SD=97) to the stereoscopic environment (M=349 seconds, SD=84.5). The increase in completion time was stronger as the task demanded more of the 3D manipulations, $F(2)=29.73$, $p<.01$. Analysis of the post-task interviews revealed that (1) students continued to employ two dimensional manipulations even when the objects were shown in the stereoscopic environment (Trindade, Fiolhais & Almeida, 2002) and (2) the cognitive load increase in the stereoscopic environment was related to the temporal and spatial contiguity principles of multimedia learning (Betrancourt, 2005; Mayer, 2005; Sweller, 2005).

Using Computer Visualizations to Connect Atomic Models to Observations on Static Electricity

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Science educators call for inquiry activities and technology-enhanced guidance to scaffold students' learning (Linn, & Hsi, 2000). Computer visualization provides a powerful means to achieve this goal (Pallant & Tinker, 2004). Research shows that computer simulations help students grasp the particle model in electrostatics (e.g., Miller, Lehman, and Koedinger, 1999). Manipulative computer simulations can engage students in learning, but not necessarily lead to enhanced understanding. This work takes advantage of an online electrostatic module to study the ideas students use at the observational and atomic levels and reports how scaffolding of interactions with computer visualizations help students connect their observations of electrostatic phenomena to accurate atomic level explanations.

The design of the module follows the knowledge integration (Linn, et. al., 2006) framework and builds on explanations of static electricity phenomena that students find in their everyday life. In the module, students investigate refueling fire incidents caused by static electricity. Students connect charge-based, atomic, and energy-based explanations to interpret their observations. They engage in laboratory activities, use dynamic computer visualizations, respond to reflective questions, and read relevant texts.

Students bring to science classrooms a repertoire of ideas about electrostatics. By analyzing students' responses to embedded assessments and notes the designers refined the instruction to guide knowledge integration. High school students in two states (N=79) studied the module. Pretests/posttests, embedded assessments, and benchmark assessments along with classroom observations and informal student interviews show that both groups of students gained integrated understanding. Students' responses to the embedded notes show that students made connections across various types of explanatory models (e.g., charge-based, atomic, and energy-based models). Their responses also reveal several patterns of how their initial ideas interact with their learning processes.

Review of Research on Dynamic Visualizations in Science Learning

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This poster synthesizes research findings on the effective design and implementation of dynamic visualizations to support students in learning science, and generates principles for designing instruction so that students benefit from their interactions with dynamic visualizations. A search of ERIC and PsycINFO yielded 224 citations. After eliminating duplicate studies and papers lacking empirical data 68 research studies remained. The studies vary with regard to the variety of students' prior knowledge or experience, the instructional practice and learning activity to support students in mindfully interacting with visualizations, and the quality of research methodology and assessment tools.

The reviewed studies employed three main approaches to designing dynamic visualizations: concept-focused approach (e.g., Windschitl, 1996), cognition-focused approach (e.g., Mayer & Moreno, 2002), and knowledge-integration approach (e.g, Linn & Eylon, 2006). All three approaches have benefits but they differ in how they remedy student difficulties in learning with dynamic visualizations. Taken together these studies and the experimental studies reported in this session lead to five design principles that have extensive empirical support. To help students connect between visualizations, phenomena, and existing personal knowledge to form an integrated knowledge framework, effective instruction uses evidence from student trials of the materials to: (1) make complex information in visualizations comprehensible, (2) make abstract and dynamic models accessible, (3) bridge abstract concepts and real-life experiences, (4) link multiple representations across contexts, and (5) make science inquiry processes explicit. To bring the principles to life, we discuss the learning difficulty the principle addresses, the design strategies have been used and their effectiveness, the instructional patterns that strengthen the principle, and the learning environment features that implement the principle. For future studies our review reveals the need to improve methods for capturing impacts of visualizations to make the revision process more effective. Methods including dynamic assessments, logging of student interactions, comparison studies showing how features of visualizations contribute to learning, and observational studies exploring student interactions with visualizations will strengthen our understanding of effective ways to take advantage of dynamic visualizations. These studies show that dynamic, interactive visualizations can dramatically improve science learning when they are carefully designed and implemented. Visualizations add value to science instruction by illustrating phenomena that are too fast, slow, complex, or small to easily observe. They succeed when embedded in instructional materials that guide students to make appropriate connections among the elements of the visualization and between the visualization and observable phenomena.

Conclusions

This session captures exciting and challenging work and will enable participants to address contentious and difficult questions facing the field, including: Are interactive visualizations important or necessary? What new opportunities do logging technologies provide for instruction and research? How can we capture students' interaction with computer visualizations? Can all learners develop meta-level skills such as self-monitoring and evaluation to guide their own interactions with dynamic visualizations? How do social interactions contribute to investigation of visualizations? Does the format of an embedded prompt impact students' experimentation strategies with dynamic visualizations? How do students connect experimentation strategies to domain knowledge? How does domain knowledge impact learning from a dynamic visualization? How do visualization task demands impact learning outcomes: can visualizations be too simple as well as too complex? How do students learn to take advantage of visualizations in general? Does experience with computer or video games contribute to success? What strategies and principles for designing instructional visualization contribute to initial design success? Which principles are most effective for refinement studies?

The presentations and discussions will provide insights into the design of effective interactive, dynamic visualizations and supporting learning activities. We expect this opportunity to spur more collaborative and cumulative investigations. We hope that presenters and participants will help shape the design principles emerging from the empirical studies. The materials are free and available for other researchers to customize and explore. The audience will add to the value of the field by critiquing the research and drawing attention to additional findings. Together we can improve science learning and develop more effective research practices.

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