Designing Effective Visualizations for Elementary School Science

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Abstract

Research has shown that technology-enhanced visualizations can improve inquiry learning in science when they are designed to support knowledge integration. Visualizations play an especially important role in supporting science learning at elementary and middle school levels because they can make unseen and complex processes visible. We identify 4 principles that can help designers and teachers incorporate visualizations into curriculum materials. These principles call for (a) reducing visual complexity to help learners recognize salient information, (b) scaffolding the process of generating explanations, (c) supporting student-initiated modeling of complex science, and (d) using multiple linked representations. We describe the principles, discuss patterns combining the principles, and give examples from several science disciplines.

Research has shown that technology-enhanced visualizations have the potential to advance learning in science disciplines such as physics (e.g., White & Frederiksen, 1998), chemistry (e.g., Dori, Sasson, Kaberman, & Herscovitz, 2004), earth science (e.g., Edelson, Gordin, & Pea, 1999; Kolodner et al., 2003), or biology (e.g., Reiser et al., 2001). However, too often, visualizations fail to realize this potential (e.g., Morrison, Tversky, & Bétrancourt, 2002). Elementary textbooks often discourage interest in science or provide experiments that lack coherence (American Association for the Advancement of Science [AAAS], 2002). To improve elementary science education, curriculum developers need to integrate new opportunities for student learning such as visualizations and encourage coherent understanding to lay the ground-
work for future learning (Roseman, Linn & Koppal, 2008). Helping students visualize basic scientific processes such as food webs, electrical circuits, or the rock cycle has great promise for elementary courses and takes advantage of modern technologies.

This article synthesizes research showing how visualizations of scientific phenomena can lead to integrated understanding. We define visualizations as any interactive representation or animation of a scientific process that permits students some form of manipulation. Examples include opportunities for students to combine virtual batteries and bulbs and to determine what closes the circuit as well as student-controlled animations of heat flow where students select the material and observe the rate of heat propagation.

We show the benefit of synthesizing design knowledge, in the form of design features, design patterns, and design principles, so that curriculum designers can use this knowledge to develop effective visualizations. This research-synthesis method captures a growing body of knowledge in this field (Kali, 2006; Kali & Linn, 2007; Linn & Eylon, 2006). We discuss how this knowledge can guide designers and how designers can contribute their experiences to a publicly accessible database of design principles.

Design knowledge is also important to teachers, who play a crucial role in the success of visualizations. Teachers can benefit from guidance about how to use visualizations effectively. Design principles can make the rationale that stands behind the design of visualizations visible to teachers, helping them think about ways to support learners and adapt visualizations to meet their classes’ needs (Davis & Varma, 2008).

We start by describing our view of learning in science as a process of knowledge integration (Bransford, Brown, & Cocking, 1999; Linn, 1995; Linn, Davis, & Bell, 2004; Linn & Hsi, 2000). We use this lens to describe the learning enhanced by various types of visualizations. We show how productive visualizations play the role of “pivotal cases” (Linn, 2005) to promote understanding and how design knowledge is gathered in the Design Principles Database (Kali, 2006) and becomes useful for designers.

To illustrate our viewpoint, we describe four design principles that can guide designers of technology-enhanced curriculum as well as teachers in generating and using visualizations effectively. We describe features of successful technologies that employ each of these design principles and report research showing that these features have helped elementary and middle school students establish a firm foundation for future science learning. We discuss the importance of embedding visualizations in a full curriculum to promote coherent understanding by describing work on effective design patterns.

**Learning as Knowledge Integration**

Science learning involves comparing, contrasting, and integrating disparate ideas (Bransford et al., 1999; Linn, 1995; Linn & Hsi, 2000; Linn et al., 2004). Learners spontaneously develop a repertoire of varied, often contradictory scientific ideas about any topic as they interact with the natural world (Linn, 1995). Students come to science class with this repertoire of multiple normative and nonnormative ideas that have emerged from their experiences. In thermodynamics, for example, students may hold a large group of ideas simultaneously. They may conclude that heat and temperature are the same because the terms can be used interchangeably: “turn up the heat,” or “turn up the temperature.” Students may rely on tactile information to decide that objects in the same room have different temperatures, concluding that metals are colder than wood at room temperature. They may assert that metal has the ability to impart cold and recommend that people wrap picnic food in aluminum foil to prevent the growth of harmful bacteria. They may decide that some materials
form barriers and prevent heat flow. At the same time, they may hold normative ideas and argue that heat flows quickly through metal because using a metal spoon to stir pasta on the stove can burn one’s hand. Knowledge integration is the process of coalescing, critiquing, augmenting, and organizing this repertoire of ideas.

To help students integrate their repertoire of ideas, successful science instruction should (a) add powerful, durable, and generative examples to their repertoire of ideas, and (b) enable students to grapple with their full repertoire of ideas to form a more coherent perspective on the scientific domain. Technology-enhanced materials that make scientific thinking visible can play an important role in both processes.

### Visualizations as Pivotal Cases

Technology-enhanced inquiry curricula can take advantage of powerful visualizations to make scientific thinking visible and improve learning outcomes (Linn, Lee, Tinker, Husic, & Chiu, 2006). Technology features that contribute to knowledge integration have been organized around four metaprinciples in the knowledge-integration framework (Linn & Hsi, 2000; Linn et al., 2004). These are (a) help make thinking visible, (b) help make the science accessible to students, (c) help learners learn from each other, and (d) promote autonomous lifelong learning (Kali & Linn, 2007).

In this article we focus on the make-thinking-visible metaprinciple. Scientific animations and visualizations can make unseen and dynamic processes such as the day/night cycle or plate tectonics visible. Students make their thinking visible, inspect their own knowledge-integration processes, and deliberately guide their learning (Bransford et al., 1999; Collins, Brown, & Holum, 1991; Linn, 1995). Designers have created and explored visualization tools that students can use to map their ideas and externalize their thoughts. Designers can also embed visualizations in inquiry environments to make complex concepts and scientific phenomena visible and understandable to young students.

Research has begun to capture the nature of visualizations that help students compare and sort out their own ideas. The knowledge-integration framework refers to successful, new additions to a student repertoire of ideas as pivotal cases (Linn, 2005). Pivotal cases are defined as examples that (a) make a compelling, scientifically valid comparison between two situations; (b) draw on accessible, culturally relevant contexts, such as everyday experiences; (c) provide feedback that supports students’ efforts to develop criteria and monitor their progress; and (d) encourage students to create narrative accounts of their ideas using precise vocabulary so they can discuss them with others (Linn, 2005). In this article we discuss how visualizations can serve as pivotal cases. Other research programs have identified knowledge elements that are similar to pivotal cases. They call these benchmark lessons (diSessa & Minstrell, 1998), bridging analogies (Clement, 1993), didactic objects (Thompson, 2002), and prototypes (Songer & Linn, 1992). Adding the right ideas to the mix students hold has the potential of dramatically increasing the efficiency and effectiveness of instruction, and visualizations offer a promising opportunity (Linn et al., 2006).

Not all visualizations serve as pivotal cases. Indeed, some visualizations can confuse students rather than assist them. Morrison et al. (2002) studied the use of animations and found that many of them do not improve learning, in part because they overload learners rather than help them sort out their ideas.

To illustrate the value of visualizations as pivotal cases, we describe how an animation called Heat Bars helped students understand insulation and conduction (Foley, 2000; Lewis, 1996; Linn & Hsi, 2000). Heat Bars allows learners to select among
varied materials of interest to them and to explore the rate of heat flow. Responding to research on student ideas, Heat Bars shows the variation in rate of heat flow, helping students distinguish among materials and providing feedback that helps clarify ideas about materials as barriers, or views that heat flows at a constant rate in all materials (Fig. 1). Heat Bars meets all the criteria for a pivotal case (Linn, 2005).

To test the effectiveness of Heat Bars, Lewis (1996) studied six classes learning thermodynamics in a single school; half used the Heat Bars simulation for about 30 minutes, and half used real-time data collection. All classes were taught by the same teacher. Lewis compared pre- and posttest performance and found an effect for Heat Bars, especially on questions about heat flow. On the delayed posttest administered 6 weeks later, students in the Heat Bars condition outperformed the comparison group.

To illustrate the importance of design decisions, we report on efforts to improve Heat Bars. Foley (2000) wondered whether the pivotal case would be more successful if it showed heat flow in color rather than black and white. He devised several versions, one using the colors commonly found in a weather map and another using red for hot and blue for cold. He found that adding color reduced the effect of Heat Bars by confusing students. The colors distracted students, making them think that heat could change color rather than just flow from warmer to colder regions. Designers of climate software report similar problems in helping learners interpret weather maps (Songer, 1996). These examples illustrate how difficult it is to design effective visualizations and show the advantage of iterative refinement. The color version did not meet the criteria of a pivotal case because it was not accessible to learners.
Design Knowledge and the Design Principles Database

The example above illustrates the importance of understanding why visualizations succeed or fail to promote learning. Such understanding is an example of a type of knowledge referred to as design knowledge—knowledge about successes and failures of using any curricular innovation in real classroom settings (Barab & Squire, 2004; Bell, Hoadley, & Linn, 2004; Collins, Joseph, & Bielaczyc, 2004; Design Based Research Collective, 2003). Several frameworks were developed to synthesize design knowledge and present it in formats that allow curriculum and technology designers to build on and further develop this knowledge (e.g., Merrill, 2002; Mor & Winters, 2007; Quintana et al., 2004; Reigeluth, 1999; van den Akker, 1999). In this article we build on the knowledge-integration framework, which captures design knowledge from 20 years of research (Linn & Hsi, 2000; Linn et al., 2004). The design knowledge in this framework is represented by the four metaprinciples mentioned above (make thinking visible, make science accessible, help learners learn from each other, and promote autonomous lifelong learning), and 14 principles that are more narrowly focused and thus more pragmatic (called pragmatic principles) that describe and illustrate how to use the metaprinciples.

To make the knowledge-integration framework more accessible and useful for designers, a Design Principles Database (http://www.design-principles.org) was developed (Kali, 2006, 2008; Kali & Linn, 2007). It contains a set of features, which are examples from diverse classroom-tested science curriculum materials, connected to the pragmatic and metaprinciples described above. Recent research has shown that the database can (a) promote collaborative knowledge building for communities who design and explore educational technologies (Kali, 2006) and (b) assist novice designers in creating effective technology-based curriculum units (Kali & Ronen-Fuhrmann, 2007). In this article, we highlight the make-thinking-visible metaprinciple.

Make Thinking Visible

We elaborate the make-thinking-visible metaprinciple by discussing four pragmatic design principles connected to this metaprinciple and by describing features from successful visualizations that employ these principles. All features are embedded in inquiry activity sequences in technology-based learning environments of various science disciplines.

Pragmatic Principle 1: Reduce Visual Complexity to Help Learners Recognize Salient Information

This principle calls for reducing the complexity of any type of visualization by eliminating functionality and details that distract from the main concept. Earlier in this article we showed how addition of colors to the successful Heat Bars animation reduced the effect of the animation (Foley, 2000). Many animations do not improve learning because they overload learners rather than pinpointing salient information (Morrison et al., 2002). In the case of Heat Bars, the new information interfered with student interpretation of feedback from the visualization.

When designing a visualization, designers need to carefully consider the sort of feedback students need. To succeed, designers need to analyze both the student repertoire of ideas and the nature of the visualization. Of course, visualizations can also oversimplify and interfere with learning. To serve as pivotal cases (Linn, 2005), visualizations need an optimal level of complexity appropriate for the specific learning goal and target audience. Finding the right balance requires characterization of the repertoire of ideas the target audience holds. In most cases, finding the right level of complexity requires several design and enactment iterations.
We illustrate how the complexity principle works in visualizations from two technology-based learning environments: BioKids (Gotwals & Songer, 2006), an elementary school ecology curriculum, and Virtual Solar System (Yair, Mintz, & Litvak, 2001), a middle school earth science curriculum.

**CyberTracker: A tool supporting biodiversity data collection in BioKids.** In this curriculum, students study biodiversity in their own schoolyard. Designed for fifth-grade students in urban Detroit, CyberTracker responds to the difficulties students have in identifying the salient features of their own empirical data. Students enter various kinds of animal data into CyberTracker based on observations in their schoolyard. By providing simple icons, which point to the type of data students are required to focus on, this feature streamlines their ability to locate and analyze relevant data. To support students’ exploration of the inquiry-fostering question (Which zone in my schoolyard has the highest biodiversity?) CyberTracker provides students with a set of common organizational visual elements representing factors such as animal abundance and animal richness (Fig. 2). This common presentation format reduces complexity and allows students to easily locate and analyze data relevant to the evaluation of the biodiversity in their schoolyard. By enabling students to compare data in a culturally relevant context, this visualization serves as a pivotal case. The use of CyberTracker helps upper-elementary students develop important scientific practices such as collecting and organizing their own data. This tool is especially effective when it is embedded in a series of activities that follow a pattern of making predictions, gathering data, interpreting results, and reconciling outcomes with predictions.

**Highlighting orbital lines in the Virtual Solar System.** Another feature that illustrates the complexity principle is employed in the Virtual Solar System—a 3D virtual reality environment for exploring the solar system (Yair et al., 2001). Using the mouse of the computer, learners can “fly” in the solar system to explore astronomic phenomena. The environment supports four modes of observation, which enable learners to change their point of view, zoom in or out, and fly around celestial objects in any direction. Navigation in this environment requires learners to make sense of the dynamic spatial information they observe. Research that explored middle school students’ use of this environment showed that they often lose a sense of orientation and find it difficult to navigate (Gazit & Chen, 2003; Gazit, Yair, & Chen, 2005; Yair et al., 2001). To facilitate this task, especially for young learners, features were added to the environment that enable students to view entities of the solar system, such as orbital lines that show the course of celestial objects (e.g., the course of the moon around the earth, or the course of the earth around the sun; Fig. 3). Although this graphic tool reduces the authenticity of the virtual environment to some extent, it has a significant advantage in helping learners overcome the loss of orientation and contributes to their understanding of the solar system (Gazit & Chen, 2003; Gazit et al., 2005). In this case, complexity stemmed from the spatial nature of the contents, which made it difficult for students to understand where they were “located” in the solar system. Adding the orbital lines provided cues for visualizing the system and reduced the complex task of spatial orientation within the solar system, which is the basic requirement for making valid comparisons among the planets. In this sense these cues make the visualization serve as a pivotal case.

**Pragmatic Principle 2: Scaffold the Process of Generating Explanations**

Generating explanations, raising conjectures, and asking questions are the essence of science. Yet, in science classes, the main communication of scientific ideas
often comes from the text, and the main rhetorical task involves clarification (Linn et al., 2004). Scaffolds can enrich the explanations learners consider and help groups of learners develop some shared criteria and standards for their explanations (McNeill, Lizotte, Krajcik, & Marx, 2006). This principle is illustrated with two features: one that elicits learners’ explanations and another than introduces a wide array of views learners hold into a discussion.

![CyberTracker Zone Summary: School Backyard](image)

<table>
<thead>
<tr>
<th>Animal Name</th>
<th>Zone A</th>
<th>Zone B</th>
<th>Zone C</th>
<th>Zone D</th>
<th>Micro Habitat</th>
<th>Tot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthworms</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>- in dirt</td>
<td>12</td>
</tr>
<tr>
<td>Other invertebrate</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>- on something</td>
<td>1</td>
</tr>
<tr>
<td>Ants</td>
<td>8</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>- in dirt</td>
<td>38</td>
</tr>
<tr>
<td>Bees</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>- in sky</td>
<td>1</td>
</tr>
<tr>
<td>Lady beetles</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>- on plant</td>
<td>4</td>
</tr>
<tr>
<td>Unknown beetle</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>- on grass</td>
<td>13</td>
</tr>
<tr>
<td>Unknown insect</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>14</td>
<td>- in sky</td>
<td>19</td>
</tr>
<tr>
<td>Unknown insect</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>14</td>
<td>- on grass</td>
<td>19</td>
</tr>
<tr>
<td>Unknown spider</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>- on grass</td>
<td>8</td>
</tr>
<tr>
<td>Centipedes</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>- on ground</td>
<td>11</td>
</tr>
<tr>
<td>Centipedes</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>- on something</td>
<td>11</td>
</tr>
<tr>
<td>Unknown bird</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>- on tree</td>
<td>9</td>
</tr>
<tr>
<td>House mouse</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>- on grass</td>
<td>1</td>
</tr>
<tr>
<td>Red squirrel</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>- on grass</td>
<td>1</td>
</tr>
</tbody>
</table>

| Number of Animals (Abundance) | 48 | 32 | 4 | 33 | 11 |
| Number of Kinds of Animals (Richness) | 9 | 2 | 3 | 4 | 18 |
Generating explanations with Principle Maker in WISE. To scaffold generation of explanations, the Principle Maker (Clark & Sampson, 2007) helps students synthesize data they have collected or experienced into a principle. It was developed as part of the “Thermodynamics: Probing Your Surrounding” WISE project for 11- to 14-year-old students (Clark & Sampson, 2007). The project uses the Heat Bars animation as well to introduce thermal equilibrium.

Using the Principle Maker, students create general principles that summarize their understanding of data collection and simulations from previous stages in the project. Students use a series of pull-down menus to construct a principle. Each menu gives a list of possible phrases from which to choose (Fig. 4). These predefined phrases represent components of principles students typically use to describe heat flow and thermal equilibrium, based on prior research.

Clark and Sampson (2007) found that scaffolding students in the creation of principles helps make student ideas explicit. Clark and Sampson take advantage of the principles students build to set up discussions that include groups with opposing ideas. They argue that this process promotes dialogical argumentation—the process of responding to ideas of others with evidence-based comments. By making student thinking visible, the Principle Maker compels students to make precise statements and enables others to formulate equally detailed reactions. Such discussions are rare in typical science classrooms. As a result, students have a good sense of the views of their peers and can spend their time supporting, evaluating, and critiquing ideas. The use of the Principle Maker encourages students to create narrative accounts of their ideas using precise vocabulary. It helps them appreciate the value of compelling explanations and gain experience responding to critiques of their ideas. In this manner it serves as a pivotal case. The Principle Maker enables learners to take advantage of the feedback from their peers because it is embedded in a WISE.
activity that guides student interactions following a promising pattern for collaboration. This form of argumentation prepares students for more advanced science courses (Linn et al., 2004).

**Sorting ideas with Idea Manager in WISE.** The Idea Manager is another WISE feature designed to guide students in making scientific explanations (Burmester & Holmes, 2005). Idea Manager is used in the Mitosis & Cell Processes module. Idea Manager has two elements. Your Ideas is an editing tool that enables students to keep track of their ideas. Users record their ideas about various issues in mitosis as they complete the activities. Ideas must be concise enough to fit on one line, but students can add as many ideas as they like. The second element, Connect Ideas, is a drag-and-drop workspace used to answer questions in a visually representative way. Students are asked to explain their answers using ideas from their list. A student can drag and drop an idea from the ideas list onto an idea workspace, producing a map of connected ideas. These ideas, now connected to different concepts, are saved as the project continues, so that by the end of the project students have a map representing their ideas. The map of interconnected ideas makes student thinking visible and enables class members to learn how others have connected ideas. It also serves as a pivotal case because it enables them to compare situations, monitor their progress, and describe, discuss, and critique their own ideas with peers and the teacher (Fig. 5). Recording ideas during a learning process, and then using these records to explain a phenomenon, is an important metacognitive skill that young learners can practice using and employ in future science courses. The Idea Manager includes not only the visual representation of ideas but also a sequence of activities that jointly help learners use the map to integrate their ideas around complex questions.

**Pragmatic Principle 3: Support Student-Initiated Modeling of Complex Science**

When students can create their own models of a phenomenon, they make decisions about how different elements of the phenomenon relate to each other. In this process they reexamine their repertoire of ideas. A major component of doing science is building computer-based models. Powerful modeling programs for students give learners the opportunity to practice building models. Researchers are beginning to create such opportunities for elementary and middle school students using tools
such as NetLogo (Colella, Klopfer, & Resnick, 2001) and Boxer (diSessa, 2000). We highlight two examples of such tools.

**Building and testing dynamic models with Model-It.** Model-It, developed at the University of Michigan, is a learner-centered tool for building dynamic, qualitative models. It was designed to support students, even those with only very basic mathematical skills, in building dynamic models of scientific phenomena and running simulations with their models to verify and analyze the results (Metcalf-Jackson, Krajcik, & Soloway, 2000). Model-It provides an easy-to-use visual structure with which students can plan, build, and test their models (Fig. 6). Model-It has been used with thousands of students and their teachers in both urban and suburban areas. Research shows that, when properly integrated into the curriculum, Model-It allows students to take part in a variety of scientific practices such as testing, debugging, building relationships, specifying variables, and synthesis (Metcalf-Jackson et al., 2000).

For instance, in one unit on water quality designed around Model-It, middle school students build models and test how pollutants would affect water quality. Exploring connections among factors that affect water quality, including the geosphere, hydrosphere, and atmosphere, can serve as a pivotal case for students and prepare them for understanding the Earth as a complex system (Ben-zvi-Assraf & Orion, 2005). The unit was especially effective because
students were guided to use Model-It following patterns such as predict-observe-explain. Additionally, such exploration can help students appreciate the nature of computerized modeling and better understand how models work.

**Building and testing electricity models in DC (Direct Current) Circuits.** The DC Circuits environment enables students to build and test circuit models by freely manipulating symbolic representations of electrical components and the wires that connect them (Fig. 7). Ronen and Eliahu (2000) found that the use of the simulation contributed to middle school students’ confidence and enhanced their motivation to stay on task, compared to a group who used real circuits. They found that the simulation provided a source of constructive feedback, helping students identify and correct alternative conceptions and cope with the common difficulties of relating formal representations to real circuits and vice versa. In this sense it acted as a pivotal case for the students. This feature shows the value of enabling students to construct their own models, as suggested by the pragmatic design principle, while embedding the activity in a pattern that includes informative feedback.

**Principle 4: Use Multiple Linked Representations**

A powerful way to illustrate a complex phenomenon is to provide students with multiple representations of the phenomenon. These can be of various types, including animations, graphs, symbolic illustrations, text, voice, and so on. Representations are not necessarily interactive and therefore are not necessarily visualizations. Using multiple representations enables diverse learners to find a representation that resonates with their ideas. Multiple representations also allow students to iden-
tify connections that are salient in one representation but not in another. Multiple representations become even more powerful when they are dynamically linked to each other and synchronized, so that changes in one representation cause appropriate changes in the other. In this manner, students can better understand connections between the various types of representations of a phenomenon and integrate ideas that each of these representations provokes, and thus these multiple representations can serve as pivotal cases. We illustrate this principle with two features from environments designed for upper-elementary and middle school earth science: the Virtual Journey within the Rock Cycle (Kali, 2003), and WorldWatcher (Edelson et al., 1999).

**Multiple representations of the rock cycle.** The Virtual Journey within the Rock Cycle is a software game designed to promote middle school students’ systems thinking in the context of the earth’s crust (Kali, 2003). Students are required to complete a mission of collecting five types of rocks (randomly assigned from a list of 15 rocks) with the least number of moves. To collect these rocks, they need to navigate to the area of formation of the rocks (e.g., shallow sea, areas of high temperature and pressure beneath the earth’s surface, etc.). Navigation is done via geological processes (e.g., weathering and sedimentation, burial and metamorphism, volcanism, etc.). The interface of the software provides learners with four interconnected views of the rock cycle system: (a) a symbolic model of the system, in which arrows represent geological processes and boxes represent their products; (b) a block diagram—a representation common in geology showing all the areas of formation of each of the geological processes; (c) a “zoom-in” view, where animation illustrates a specific geological process; and (d) a text box explaining the geological process (Fig. 8). Each time a student...
navigates to a different area of rock formation, the four views change simultaneously to illustrate various aspects related to that area. To collect the five types of rocks, students need to pass through several cycles of rock-forming processes. This type of activity has been shown to promote students’ understanding of the earth’s crust as a cyclic system (Kali, 2003). Such understanding is a crucial foundation for students’ further learning in earth science, specifically, for understanding plate tectonics (Kali, Orion, & Eylon, 2003). Students using the game are motivated not only to understand the location of the specific rocks but also the explanation for their formation. The game also guides students to hypothesize, test their ideas, and combine their findings.

**Multiple representations in WorldWatcher.** WorldWatcher is a supportive scientific visualization for the investigation of weather data. It is based on features used in powerful, general purpose tools for scientists that were adapted for the use of students (Edelson et al., 1999). WorldWatcher is used in the Planetary Forecaster Project (grades 6 to 8) where students explore the major factors that lead to variations in temperature around the globe. The project places students in the role of research scientists who must investigate the causes of temperature variation on Earth in order to make temperature predictions (and, in turn, identify habitable areas) on a fictional, newly discovered planet.

WorldWatcher displays two-dimensional global data in the form of color maps. To provide geographical context, it displays them with latitude and longitude markings and an optional continent outline overlay. A constantly updated readout follows the user’s mouse as it travels over an image, displaying the current latitude, longitude, country or state/province, and temperature data value (Fig. 9). In this manner, the different types of representations of the data (i.e.,
Discussion

The examples we have presented show how visualizations can help students integrate their ideas. Visualizations often serve as pivotal cases, illustrating an idea that stimulates learners to reconsider their prior knowledge. As we have illustrated, successful visualizations are typically embedded in promising instructional patterns that highlight salient information and guide knowledge integration. For example, patterns prompt learners to generate explanations, compare their results to those of peers, design a model, link varied representations, or reflect on alternatives. The principles guide the design of the visualizations, but the visualizations succeed because they are implemented as part of powerful patterns.

To support designers as they create...
such sequences and embed visualizations in them, Linn and Eylon (2006) have identified design patterns to complement the design-principles approach. A design pattern is a sequence of activities teachers and students in a classroom follow. Linn and Eylon (2006) synthesized a broad range of research on inquiry science to identify patterns that employ knowledge-integration processes in productive ways.

An example of using visualizations within a sequence of activities can be found in the work of Clark and Sampson (2007). In their “Thermodynamics: Probing Your Surrounding” unit, they used two of the features we described—a revised version of Heat Bars called Heat Flow Simulation, and the Principle Maker, in a sequence of activities that was guided by a design pattern called predict, observe, explain (Linn & Eylon, 2006; initially described by White & Gunstone, 1992).

The predict, observe, explain pattern involves providing students with a demonstration of a scientific phenomenon. The pattern starts with eliciting students’ predictions, then running the demonstration, and, finally, asking students to reconcile contradictions (White & Gunstone, 1992). To contribute to knowledge integration, the predict, observe, explain pattern engages students in testing conjectures. The use of the pattern strips away some of the complexities of a scientific phenomenon by providing a demonstration and encouraging careful observation. Research has shown that observing a demonstration is less effective than interaction with it (Crouch & Mazur, 2001). The explain step in the pattern compensates by encouraging learners to articulate any discrepancies between their prediction and the outcome.

Guided by this design pattern, Clark and Sampson (2007) developed the thermodynamics unit starting with a driving question that elicits students’ ideas about thermodynamics: People talk about objects being “naturally hot” or “naturally cold.” What do they mean? Then, students make predictions about the temperature of various objects in the room and measure the temperature of these objects to compare with their predictions. To explain their findings, they explore the heat-flow simulation that shows heat transfer between a hot cup and a warm table at both the observable and molecular levels. Students then use the lenses of rate of cooling as a basis for understanding the concepts of insulators and conductors. The culminating activities engage students in developing principles that explain everyday phenomena related to heat transfer and in critiquing principles created by their peers.

The use of the predict, observe, explain pattern assisted the designers in tailoring a sequence of activities that embeds the heat-flow simulation within other features that employ, in addition to the make-thinking-visible metaprinciple, other metaprinciples as well (i.e., make science accessible, help learners learn from each other, and promote autonomous lifelong learning). Asking students to make predictions about the temperature of various objects in the room helps make science accessible by building on student knowledge and using examples that are familiar to students from their everyday experiences. The peer critiquing of the principles created by other students in the culminating activity enables students to learn from each other, as well as to develop critiquing skills. These skills might encourage students to continue to critique any information they encounter in their future schooling and everyday life.

Conclusions

Visualizations offer great promise for designing technology-based environments that support students’ learning of science. They can provide students with powerful new ideas that can help them sort their existing views of a scientific phenomenon and promote a more coherent generative view of this phenomenon. They can also provide a robust basis for further science
learning by diverse learners in higher grades. However, for visualizations to serve as pivotal cases, they need to be carefully designed based on design knowledge such as design principles and design patterns. Design principles can guide designers in creating innovative visualizations that build on past failure and success stories, and design patterns can assist designers in embedding these innovations in appropriate activity sequences, tailored for specific needs and requirements of the field. As we discussed earlier, to enhance their effectiveness, the rationales considered when designing any feature in a learning environment should be made visible to teachers, who need this knowledge to help their students maximize the benefit from learning environments.

Note

This article is based on work supported by the National Science Foundation under grant nos. REC-0311835, ESI-0334199, and ESI-0455877. Any opinions, findings, and conclusions or recommendations expressed are ours and do not necessarily reflect the views of the National Science Foundation. We benefited from helpful conversations with the Technology-Enhanced Learning in Science Group and the Design Group at the Department of Education in Technology and Science at the Technion–Israel Institute of Technology. We thank all those who contributed from their design knowledge and experience to the Design Principles Database. Finally, we appreciate help in production of this article from Jonathan Breitbart.

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