CHAPTER 12: TECHNOLOGY-ENHANCED SUPPORT STRATEGIES FOR INQUIRY LEARNING

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ABSTRACT

Design studies provide evidence for the effectiveness of specific supports for learning in technology-enhanced environments, and suggest guidelines for the design and use of such features. The Design Principles Database is a public collaborative knowledge building tool that helps capture and synthesize this knowledge using "design principles" as a basic construct. In this chapter we highlight eight pragmatic design principles from the Design Principles Database, which are most likely to support learning, and provide evidence that shows how learning is supported by features in technologies that apply these principles. We discuss the advantages and limitations of design principles to guide a design process, and suggest that in order for design principles to be more effective for guiding new innovations, they should be complemented with a design patterns approach.

Keywords:

Design principles: Research-based guidelines for instructional design. Design principles can be articulated at different grain-sizes: specific principles characterize rationales for designing specific features in a learning environment; pragmatic principles connect rationales behind several features; meta-principles synthesize a cluster of pragmatic principles.

Knowledge integration: The process of adding, distinguishing, organizing, and evaluating accounts of phenomena, situations, and abstractions.

Learning environment: A system that incorporates a set of features including a navigation system. Learning environments can deliver curriculum in any topic area.

Software features**:** Specific applications of technology intended to advance learning. Features include designed artifacts such as modeling tools, simulations, micro-worlds, visualizations, collaboration tools, reflection prompts, games, and embedded assessments.

12.1 INTRODUCTION

This paper synthesizes the benefits of technology-enhanced supports for inquiry learning and is intended to help designers build on past work, and help researchers report new findings in the context of current work. To achieve these goals, we take advantage of efforts to collate design principles, such as those devised by Brown (1992), Kali, (2006), Kali (in press), Merrill (2002), Quintana et al., (2004), Reigeluth (1999) and Van den Akker (1999). We draw on current views of the learner informed by research in cognition and instruction (Bransford, Brown, & Cocking, 1999; Linn, Davis, & Bell, 2004).

Designers have created and refined numerous supports for inquiry learning. We define support strategies as features of technology-enhanced instruction that the designers report contribute to learning such as guidance, prompts for reflection, and varied representations of content. We define inquiry broadly to refer to any activity that engages the learner in exploring a scientific phenomenon. These supports are embedded in many technology-enhanced inquiry programs that have been tested in classrooms (e.g., Barab et al., 2000; Bruer, 1993; diSessa, 2000; Edelson, Gordin, & Pea, 1999; Krajcik et al., 1998; Means, 1994; Reiser et al., 2001; Roschelle, et al., 2000; Linn, Clark, & Slotta, 2003; Scardamalia & Bereiter, 1996; Schwartz, Brophy, Lin, & Bransford, 1999; Songer et al., 2003, Tinker, 2005; White & Frederiksen, 1998).

Studies of inquiry learning show that learners grapple with multiple, conflicting, and often confusing, ideas about scientific phenomena. Successful supports for inquiry help learners identify their repertoire of ideas by engaging them in multiple, often authentic problem situations. Successful technology enhanced instruction often takes advantage of models, simulations, or visualizations to introduce new ideas. Effective instruction does not stop with eliciting and adding ideas, however. To gain durable, generative understanding, students need to devise criteria for sorting out these ideas in varied contexts and at multiple levels of analysis. They need supports that allow them to formulate, often in collaboration with others, more and more nuanced criteria for evaluating ideas. They need time to sort out their ideas and develop an increasingly linked set of views about any phenomenon. In this chapter we synthesize recent research using technology-enhanced curriculum materials to support inquiry. We identify promising supports for inquiry that emphasize all four processes: eliciting ideas, adding ideas, developing criteria, and sorting out ideas. These processes are the main elements of the knowledge integration framework (Linn, 1995; Linn & Hsi, 2000; Linn, Davis, & Bell, 2004).

Designers often find building on past successes challenging because studies do not tease apart the consequential elements of the innovation (e.g., Cognition and Technology Group at Vanderbilt, 1997). We seek ways to facilitate effective use of technology in science learning. In spite of extensive research on supports for inquiry learning, most uses of technology for precollege instruction use drill and practice, word processing, and web-surfing (Fishman et al., 2004). University instruction primarily relies on web delivery of information (Herrington, Reeves & Oliver, 2005). Mioduser and colleagues (1999), summarize current uses of technology in education as "One step ahead for the technology, two steps back for the pedagogy" (p.757).

To identify promising elements of supports for inquiry, we synthesize findings from design research. Design researchers conduct iterative refinements to develop successful innovations (Bell, Hoadley & Linn, 2004; Design-Based Research Collective, 2003; Simon, 1969). Studies comparing alternative designs or sequences of refinements provide evidence for the effectiveness of specific supports, shed light on the mechanism behind supports, and suggest guidelines for implementation. These studies often summarize findings in design principles, learning principles, patterns, and related synthesis methods to capture both the innovations and the mechanisms that govern their success. Brown (1992) offered learning principles to synthesize her research findings. Collins (1992) called for guidelines to capture research-based practical design knowledge. These efforts echo practices in other design-based fields that have found principles helpful, including architecture (Alexander et al., 1977), graphical communication (Tufte, 1983), and computer science (Gamma et al., 1995).

The current synthesis starts with features of inquiry innovations captured by Kali (2006) and Kali (in press) in the Design Principles Database (http://www.design-principles.org). The current entries in the Design Principles Database represent the contributions of over 50 individual researchers. The database includes more than 70 features (mainly from physical, life, and earth sciences.) The database connects (a) descriptions of promising features, (b) the rationale for the feature, and (c) evidence for the impact of the feature to pragmatic design principles. Pragmatic principles are abstracted guidelines that connect similar rationales behind features in different learning environments. Although features are entered in the database as independent entities, they are often parts of sequences of features that comprise a learning environment.

The database is organized around meta-principles. Meta-principles are overarching ideas that synthesize a cluster of pragmatic principles. The meta-principles in the database are: Make thinking visible, make science accessible, help learners learn from each other and promote autonomous lifelong learning.

The structure of the Design Principles Database emerged from longitudinal research on technology-enhanced science learning (Linn & Hsi, 2000; Linn, Davis, & Bell, 2004). The Computer as Learning Partner research program identified the 4 meta-principles and the first 14 pragmatic principles in their 20 year long effort to iteratively refine effective interactive science experiences (Linn & Hsi, 2000). The Design Principles Database has grown with contributions from participants in workshops, from course activities, and from the public (Kali et al., 2002). It serves as a collaborative knowledge building tool for communities who design and explore educational technologies (Kali, 2006). The Design Principles Database enables designers to explain the pedagogical rationales behind each feature in a learning environment and for community members to respond and add their experiences. It is based on the idea that explaining the rationale of a feature can be useful for other designers. Researchers have added additional principles (Linn, Davis, & Bell, 2004) and applied the ideas to design of assessments (Clark & Linn, 2003), professional development (Williams & Linn, 2003), and learning environments (Linn, Clark, & Slotta, 2003). Researchers can explore the application of principles in new contexts and add their findings back to the Design Principles Database. The design knowledge grows as principles are debated, refined, or warranted with additional field-based evidence.

12.2 SUPPORTS FOR INQUIRY LEARNING

To synthesize supports for inquiry learning, we start with the four meta-principles in the Design Principles Database and select pragmatic principles that connect with the largest number of software features. We highlighted two promising features for each pragmatic principle. The features vary in their grain-size; some represent whole learning environments (such as Model-It), some represent tools in a learning environment (such as the inquiry map in WISE), and others represent elements in software (such as the manipulative animated 3D illustrations in Geo3D). Table 12.1 shows the features, and their connection with pragmatic and meta-principles. We describe the meta-principle, associated pragmatic principles, and illustrative features to characterize supports for inquiry learning.

Table 12.1: Features described in paper and their connections to pragmatic and meta-principles

Pragmatic Principles	**Features**
Meta-principle: Make Science Accessible	
○ Communicate the diversity of science inquiry	○ Inquiry map in WISE ○ SenseMaker in WISE
○ Connect to personally relevant examples	○ Authentic contexts in the Jasper project ○ Contextualized definition in TELS
Meta-principle: Make Thinking Visible	
○ Provide students with templates to organize ideas	○ Principle maker in WISE ○ Design Rule of Thumb template in SMILE
○ Provide knowledge representation tools	○ Model It ○ Causal Mapper
○ Enable 3D manipulation	○ 3D illustrations in Geo3D ○ Scaffolds to support student use of molecular modeling software
Meta-principle: Help Learners Learn from Each Other	
○ Encourage learners to learn from others	○ Automated gathering of peer-evaluation outcomes in CeLS ○ Supports for collaboration in eStep
Meta-principle: Promote Autonomous Lifelong Learning	
○ Enable manipulation of factors in models and simulation	○ Manipulable models of molecules in Molecular Workbench ○ Modeling derivatives in Visual Mathematics
○ Encourage reflection	○ Prompts for reflection-on-action in CASES ○ Note-taking in WISE

12.2.1 Meta-principle: Make Science Accessible

Designers seek to make science accessible for learners to elicit the full repertoire of ideas. They create supports that increase the relevance of science for all learners – those aspiring to careers in science and those taking their last science course. These supports respond to the common complaint that science is not relevant or useful. They also remedy the often inadequate images of science held by students (Hofer & Pintrich, 2002). Two pragmatic principles that follow this meta-principle call for communicating the diversity of science inquiry and for connecting to personally-relevant examples.

12.2.1.1 Pragmatic principle: Communicate the diversity of science inquiry

This principle calls on designers to expose learners to the rich diversity of the inquiry process. Far too often students leave science class with an image of inquiry as dogmatic and inflexible or abstract and incomprehensible (Linn, Bell, & Davis, 2004). Technology-enhanced learning environments can help students become aware of the diversity of science inquiry by engaging students in a variety of inquiry processes. We exemplify how this principle is applied in two different features that are part of the Web-based Inquiry Science Environment (WISE) (Slotta, 2004).

Inquiry map in WISE. To help students explore inquiry processes, WISE uses an inquiry map, which is a dynamic-graphic guide shown in each of the WISE projects (Figure 12.1). It graphically represents the steps of the inquiry in the project. This enables students to get an overview of the project and the inquiry strategies it includes. The inquiry map also expands and collapses each project into its main inquiry components. Teachers using WISE indicate that the map makes students more independent in their inquiry activities – strengthening their understanding of the diversity of inquiry processes. In many cases the inquiry map provides answers to *What do I do now?* questions, making the inquiry process more self-directed. The map also helps students get a better understanding of how each step in the project relates to the whole inquiry process (Linn & Hsi, 2000).

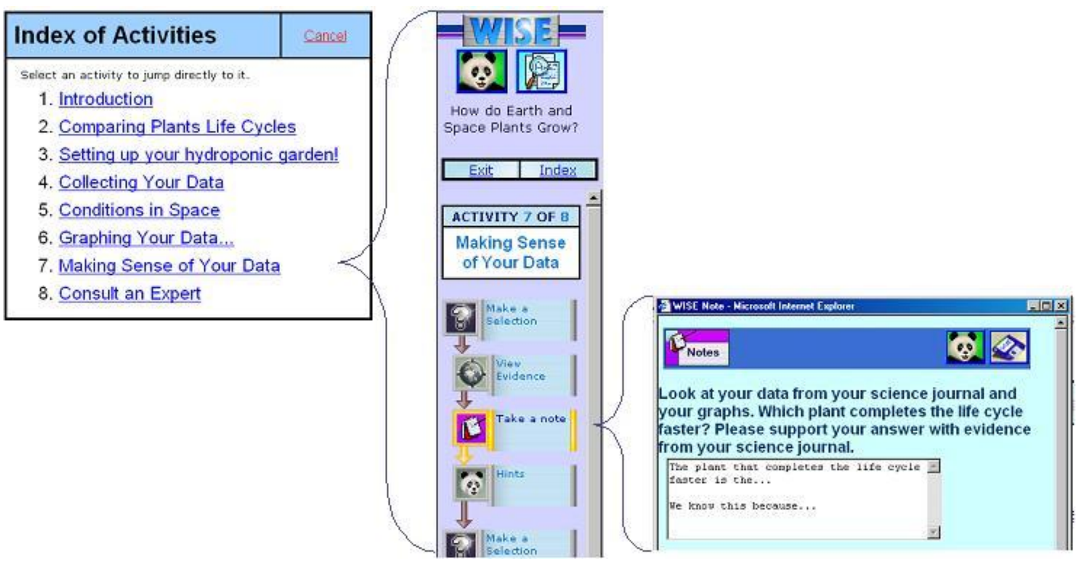

Figure 12.1: WISE inquiry map (in middle) with index of activities (left) and reelection note (right).

SenseMaker in WISE. Another feature that communicates the idea of diversity in science inquiry engages students in controversial scientific debates

(Bell, 2004). The WISE SenseMaker tool (Figure 12.2) helps students figure out the relationships that exist between different Web resources. As they investigate pieces of Web-based evidence, students organize the items into categories in SenseMaker. This sorting of pieces of evidence helps students consolidate their own stance about the controversy and prepare for a class debate. During the debate, the graphical representations of student arguments are displayed. Students can see the diversity of inquiry strategies by comparing their arguments to those of other students and of experts (Bell, 2004).

SenseMaker can support debates about issues, like the threat of malaria. Students explore the ethical trade-offs between protecting human life (by spraying DDT) and protecting wildlife and the environment (by banning the use of DDT), (Seethaler & Linn, 2004). Research shows that engaging students in such debates and supporting their inquiry process with SenseMaker can help students develop a more integrated understanding of complex science topics (Bell, 2004).

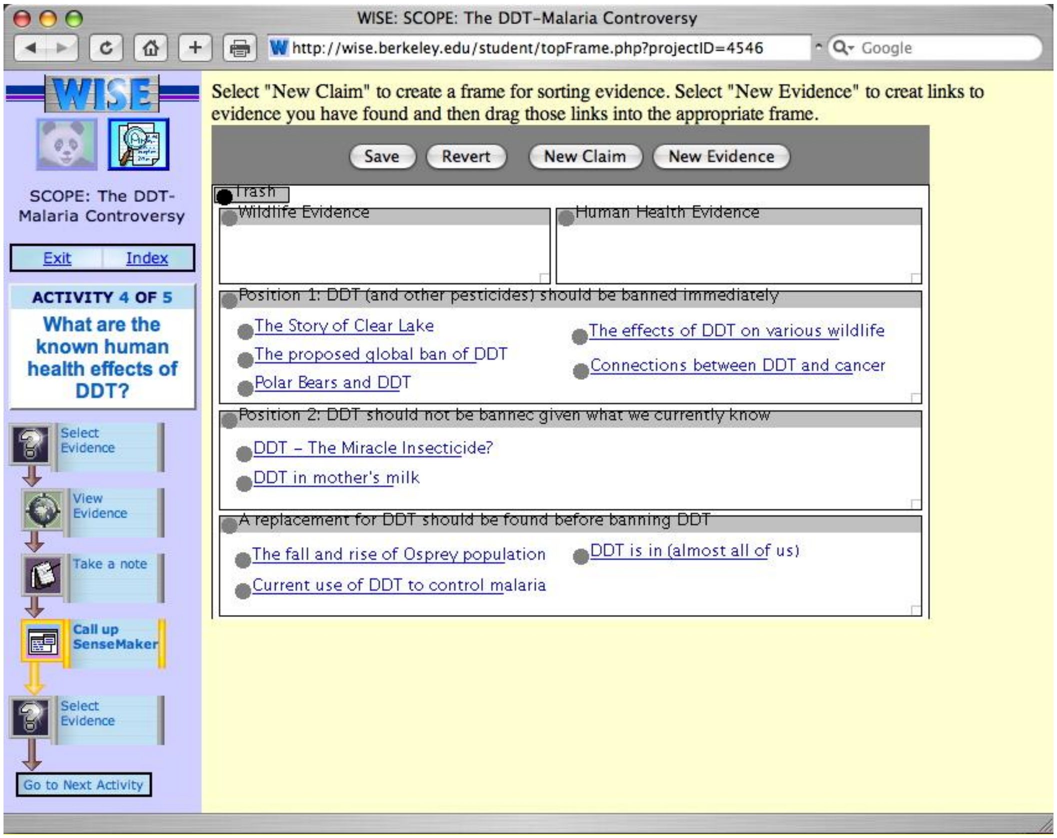

Figure 12.2: Sorting of evidence web-pages in SenseMaker.

12.2.1.2 Pragmatic principle: Connect to personally relevant examples

Personally-relevant problems such as determining how to keep a drink cold make science accessible because they elicit intuitive ideas to fuel inquiry (Linn & Hsi, 2000; Songer & Linn, 1991). Linn, Davis, and Bell (2004) show that eliciting the broad range of student ideas about science and engaging these ideas enables students to build more coherent, durable scientific views. This principle advocates using personally relevant examples as contexts for scientific inquiry. The examples below show how this principle was applied by two research groups.

Authentic contexts in the Jasper project. The Jasper project, using the anchored instruction approach (Cognition and Technology Group at Vanderbilt, 1990; 1997), was one of the earliest large endeavors to use technology to anchor instruction in authentic contexts. Jasper includes a set of 12 video-based adventures that focus on mathematical problem solving. Each video ends in a complex challenge. The adventures are designed like good detective novels, in which all the data necessary to solve the adventure are embedded in the story. The Jasper adventures present a believable story that has interesting characters, a complex and important challenge, and extensions to a variety of curricular areas. To solve the challenge, the students combine problem-solving skills, mathematics concepts, and the information in the video. The Adventures were designed to bridge the gap between everyday and school problems. They provide a common context for instruction, an authentic task, and a chance to see that school knowledge can be used to solve real problems.

Contextualized definitions in TELS modules. The Technology Enhanced Learning in Science (TELS) “Hanging with Friends - Velocity Style!” module (Tate, 2005), embeds scientific terms in the context of an interview with a teenager. The purpose of the interview is to find the teenager’s velocity, but the context of the interview is her trip from Lake Park to the movie theatre to meet her friends. The interviewee speaks in everyday language while communicating the information needed to determine her velocity, saying, “I was running a bit late and almost didn’t get a seat. I arrived at the Movie Theatre at 5:05 pm. This is referred to as my final time.” The discourse blends everyday language and events (being late to a movie) with information needed to determine velocity. By bringing everyday events (a conversation or interview) into play, the feature draws students into the activity and helps them place it in a familiar context. They compute the velocity of each friend to see if all will arrive in time. The feature motivates students to understand the specific terms and data needed to compute velocity for an everyday event.

12.2.2 Meta-principle: Make Thinking Visible

To promote inquiry, designers often encourage students and teachers to make their thinking visible. When students make thinking visible, they can inspect their own knowledge integration processes and deliberately guide their learning (Bransford, Brown, & Cocking, 1999; Collins et al., 1991; Linn, 1995). To support these processes, designers create tools that students use to map their ideas and externalize their thoughts at different stages of the learning process. Designers also use models or visualizations embedded in inquiry projects to make complex concepts and scientific phenomena visible. We highlight three pragmatic principles that follow this meta-principle. The first two are intended to help students make their own thinking visible, and the third is intended to make complex scientific phenomena visible. We exemplify each pragmatic principle with two features from different contexts.

12.2.2.1 Provide students with templates to organize ideas

To support students in articulating complex scientific ideas, designers have created what might be called templates. Templates scaffold students in representing their ideas and revising them as they complete complex activities (Kolodner et al., 2004). Below are two examples that show software features from two contexts that apply this principle.

Principle Maker in WISE. One feature that exemplifies how templates can help organize ideas, is the Principle Maker (Clark & Sampson, in press). The Principle Maker (Figure 12.3) is a tool in the WISE environment that helps students synthesize data that they have collected or experienced into a principle. By providing building-block phrases, the tool scaffolds the task and gives students clear alternatives without dictating ideas. The Principle Maker is part of a TELS project called “Thermodynamics: Probing Your Surroundings.” Research conducted by Clark and Sampson (in press) suggests 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, a feature found under the learn from each other meta-principle. By making thinking visible the principle maker enables a more sophisticated form of argumentation than found 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.

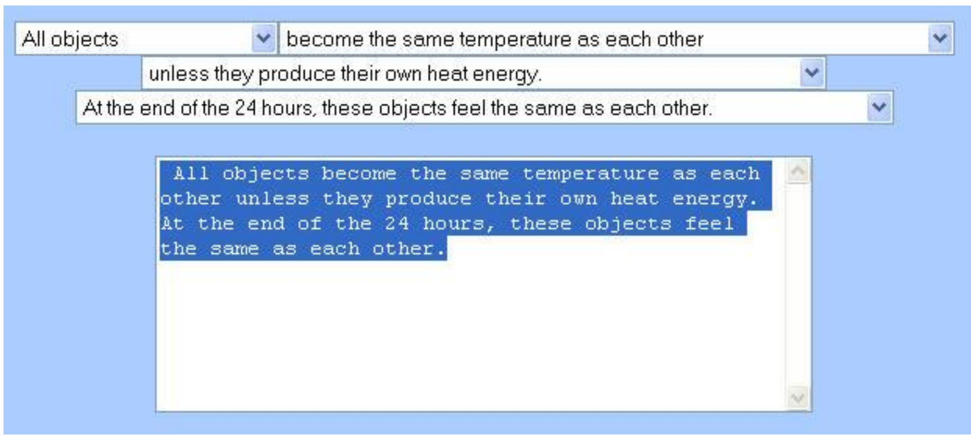

Figure 12.3: Scaffolding students in the creation of principles with Principle Maker.

Design Rule of Thumb template in SMILE. Another feature designed according to this principle is part of the Learning by Design classrooms, and the Supporting Multi-user Interactive Learning Environment (SMILE) (Kolodner, et al., 2004) . This feature assists students to generate and then revise design-rules-of-thumb throughout a project experience. Design rules-of-thumb are lessons that are learned from experience. The template includes constructs that help students construct a design-rule-of-thumb, in the following format: When/If (describe the action, design, or choice you are working within) use/connect/build/employ/measure (list your suggestion or method) because (list or supply the evidence or science principle or concept that backs up your suggestion) (Figure 4). Students initially attempt to generate these rules-of-thumb in small groups based on their experimental results or on cases they are reading. They discuss the rules-of-thumb as a class and revise them. Ideally, students notice ideas they cannot explain, and identify the science they need to learn. Research shows that before use of the template, students were often unable to make the appropriate connections to science. When templates were used in the context of a class, teachers were better able to introduce the appropriate scientific concepts. When the teacher helped students create rules-of-thumb as a class before using the software, students using the software created better rules-of-thumb (with a richer situation description and justification) than students who did not have the template available in the software (Kolodner et al., 2004).

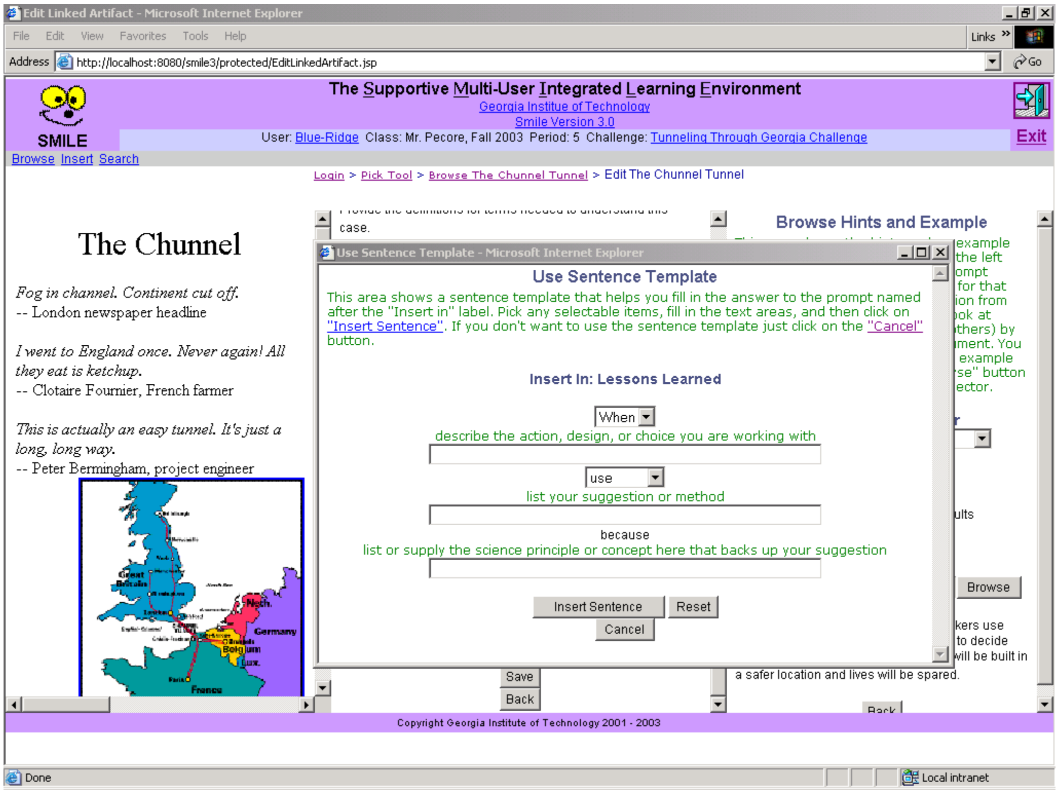

Figure 12.4: Design rule of thumb template in SMILE 12.2.2.2 Pragmatic principle: Provide knowledge representation tools.

This principle calls for providing learners with tools in which they can visually represent, at different learning stages, their understanding of scientific ideas. Linn, Davis and Bell (2004), claim that knowledge representation tools can promote interpretation and theorizing about evidence.

Model-It. An example of a tool that enables students to represent and test their knowledge is Model-It, developed at the University of Michigan. Model-It is a learner-centered tool for building dynamic, qualitative based models. Model-It was designed to support students, even those with only very basic mathematical skills, building dynamic models of scientific phenomena, and running simulations with their models to verify and analyze the results (Jackson, Krajcik, & Soloway, 2000). For instance, students can build models of water quality and then test how various pollutants would affect water quality. Model-It provides an easy-to-use visual structure with which students can plan, build and test their models (Figure 5).

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 (Jackson, Krajcik, & Soloway, 2000).

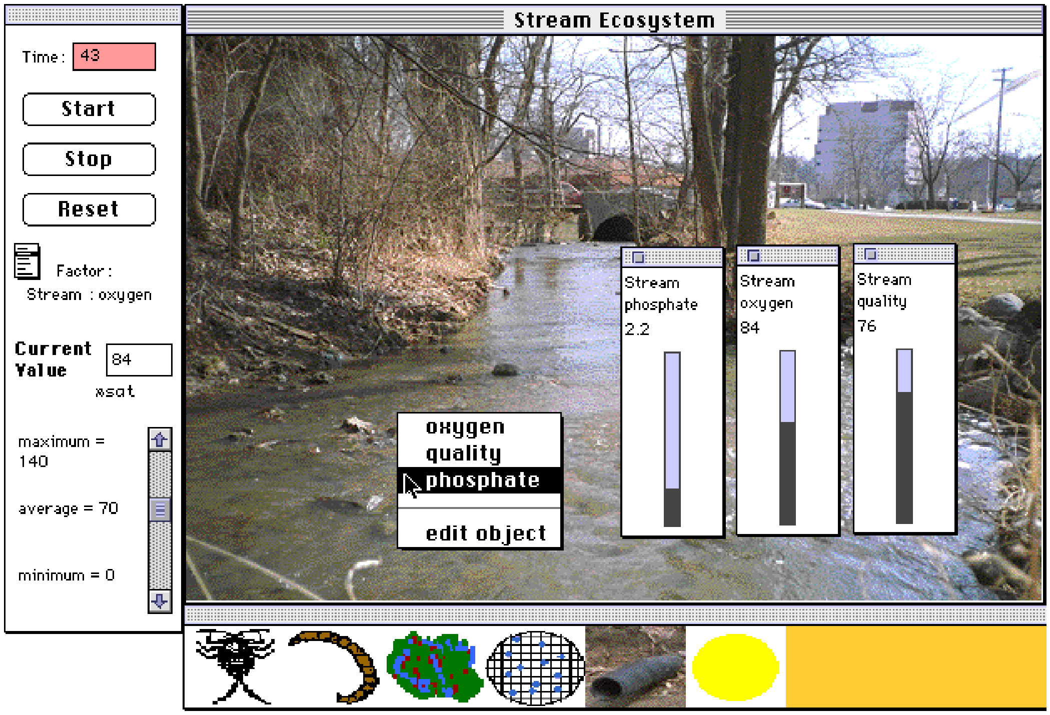

Figure 12.5: Running a simulation built by students in Model-It

Causal Mapper. Another example of a feature that enables students to represent their understanding is Causal Mapper. This feature, developed by Baumgartner (2004), is a standalone application that allows learners to make sense of a set of causal relationships. Causal mapping refers to the use of directed node and link graphs -- similar to concept maps in some ways -- to represent a set of causal relationships within a system. For example, the causal map in Figure 12.6 reflects two sixth grade girls representation of the factors that contribute to the health of a stream. Causal mapping is more structured than concept mapping, in that links capture causal relations. Students can develop a shared representation for causality, and groups can quickly examine and critique each others' causal maps, and discuss complex causal chains. Baumgartner (2004) shows that when students map their own data using causal mapper, they develop their ability to interpret their data and use it as evidence for their investigations.

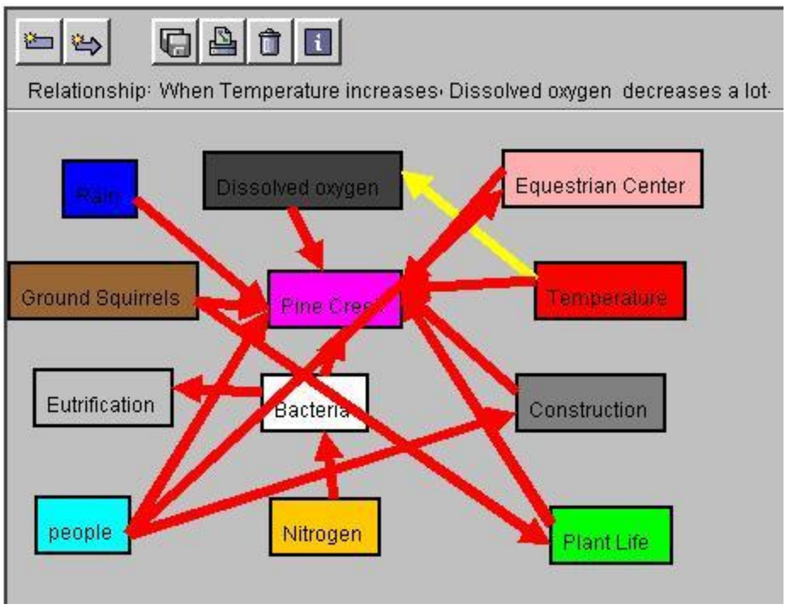

Figure 12.6: Map created by students with Causal Mapper to represent water quality factors

12.2.2.3. Pragmatic principle: Enable 3D manipulation

In the description of the make thinking visible meta-principle above, we mention that one aspect is animating complex scientific phenomena. Enable 3D manipulation is a pragmatic principle that emphasizes making scientific phenomena visible. Many students have difficulty perceiving 3D structures, which are presented in textbooks as 2D representations. Technology can provide tools that enable students to manipulate representations of these structures. Visualizations can enable students to rotate objects being studied and thus view them from various directions (e.g., Dori, Barak & Adir, 2003; Hsi, Linn & Bell, 1997; Kali, Orion & Mazor, 1997). Other types of 3D visualizations can also improve understanding, as described in the following two features:

3D illustrations in Geo3D. Geo3D was designed to respond to the spatial abilities required in structural geology, and the difficulties that high-school students have in the perception of geological structures (Kali & Orion, 1996). In Geo3D, students can visually bisect illustrations of geological structures (see Figure 12.7). They explore relationships between observable and unseen properties of the geological structures. These relationships strengthen perception of geological structures created by folding, uplifting and erosion (Kali, Orion & Mazor, 1997). Even short interactions with these animations (1-2 hours) improves students' skills in visualization of geological structures.

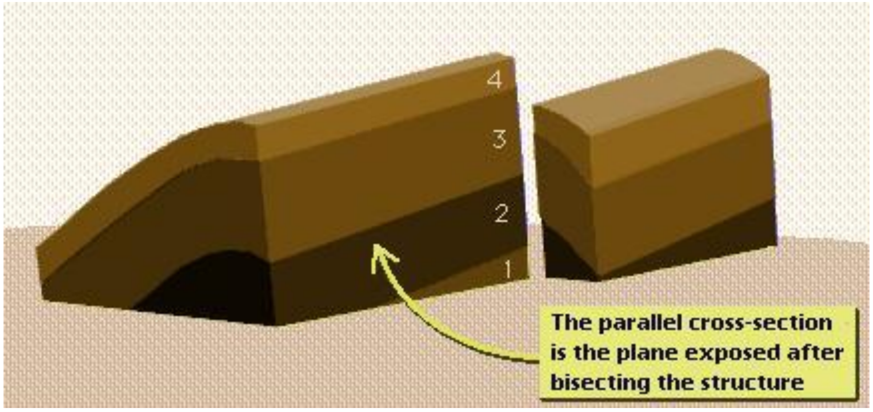

Figure 12.7: Animation that shows bisection of a geological structure in Geo3D.

Scaffolds to support student use of molecular modeling software. Many students have difficulties relating symbolic representation of molecules to 2D and 3D models, especially when organic compounds are involved. Dori et al., (2003) and Barak and Dori (2005) designed a suite of activities, which take advantage of molecular modeling software originally designed for experts, such as WebLab Viewer and ISIS-draw. To use software designed for experts, learning materials need to highlight the salient information for students (Edelson, Gordin & Pea, 1999). Guided by this suit of activities, students construct 2D representations of chemical substances using ISIS-draw, and then use Weblab to transform the 2D representations into a 3D (framework, ball-and-stick, or space-filling) image (Figure 12.8). Students compare their representations to those of their peers. Dori et al. (2006), show that these activities increase students' understanding of the physical and chemical properties of simple and complex compounds.

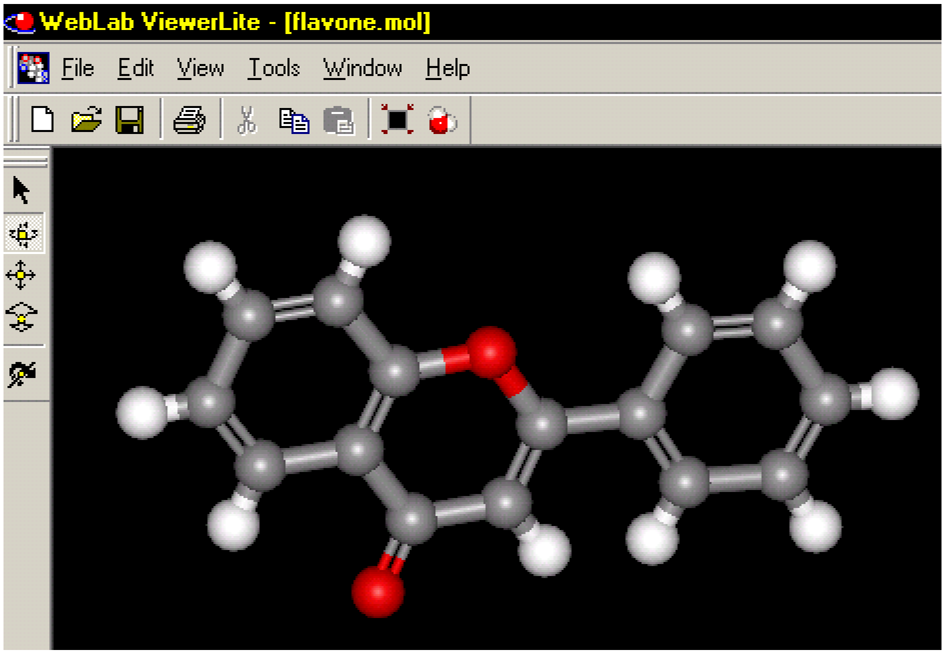

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Figure 12.8: Ball and stick model created by a student using the scaffolding activities for the WebLab tool.

12.2.3 Meta-Principle: Help Learners Learn from Each Other

To help students develop criteria and distinguish among ideas, designers embed social supports in inquiry activities. These opportunities encourage students to listen and learn from others and take advantage of the collective knowledge in the classroom community. Encouraging students to analyze and build on ideas from peers can introduce new perspectives and motivate students to form criteria (Scradamalia & Bereiter, 1994). Additionally, when students interact, they bring to light the alternative views held by learners and the criteria used to interpret ideas (Bransford et al., 1999). We highlight one pragmatic principle that follows this meta-principle, and describe two features that show its use in different contexts.

12.2.3.1 Pragmatic principle: Encourage learners to learn from others

This principle emphasizes helping learners to listen and learn from others. When students explain their thoughts to other students, they sort out their own ideas, and learn new ideas from others. Students can help their peers understand an idea by articulating concepts using familiar vocabulary and relevant examples.

Automated gathering of peer-evaluation outcomes in CeLS. One example of this principle involves automating peer evaluation. CeLS (Collaborative, e-Learning Structure) (http://www.mycels.net) enables instructors to construct online structured collaborative activities, including peer-evaluation. CeLS automatically gathers and analyses information submitted by students and shows it in various customizable forms. Figure 12.9 shows an example of the type of information that can be presented in a peer evaluation activity designed in CeLS, including statistical analysis, a histogram, and a collection of student justifications for their grading (presented anonymously). Kali and Ronen (2005) used a peer-evaluation activity designed with CeLS in a philosophy of education course. Undergraduate students constructed a conceptual model of their “ideal school” and developed more sophisticated epistemologies, as a result of peer evaluation.

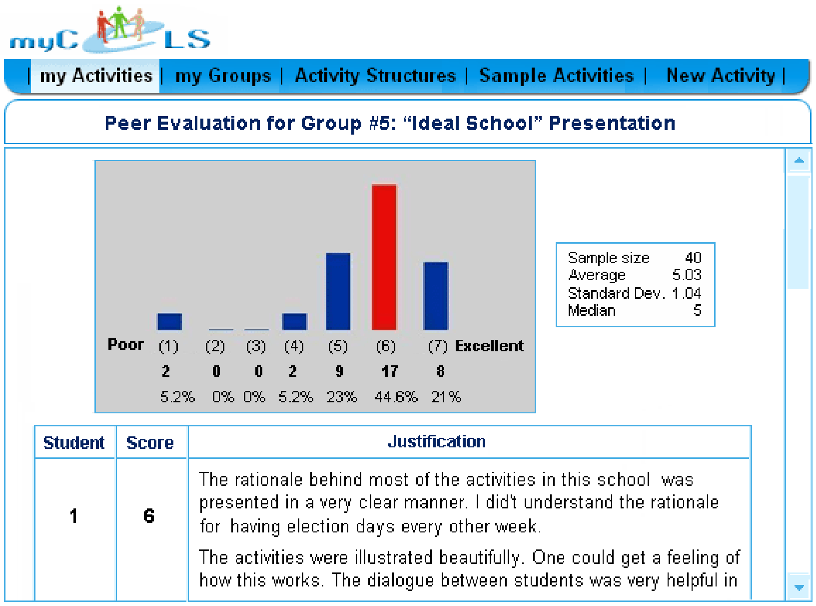

Figure 12.9: Peer evaluation activity designed with CeLS.

Supports for collaboration in eStep. Another example of technology supports that encourage learners to learn from others is the eStep system (Hmelo-Silver et al., 2005; Derry, et al., 2005). In eStep learners read and view a case study that presents a classroom dilemma. They individually reflect on the dilemma and propose an initial solution. Then they collaborate with other learners to collectively arrive at a revised solution. The lesson ends with individual critiques of the group solution, and reflection on the learning, collaboration, lesson design, and usefulness of the solution to their own professional practice. Derry, et al. (2005) report that eStep produced significant increases in teacher-learners' abilities to think deeply about student understanding and that the course was more effective at producing transfer than a traditional lecture-based approach covering the same material.

12.2.4 Meta-principle: Promote Autonomous Lifelong Learning

To become lifelong learners, students need supports that help them guide their own learning, recognize new ideas, and develop a view of effective inquiry. They need to engage in sustained project work so they can connect personally relevant problems to class topics, and reflect on experience using a robust inquiry process in diverse contexts (Linn, Davis, & Bell, 2004). Students benefit from learning to monitor their progress. To encourage autonomy, designers scaffold comprehensive inquiry processes that students can apply to varied problems both in class and throughout their lives and explore ways to ensure that these practices are internalized. We present two pragmatic principles from the Design Principles Database that apply this meta-principle, and exemplify each, with two features.

12.2.4.1 Pragmatic principle: Enable manipulation of factors in models and simulations

Interactive models, simulations, and visualizations support autonomy, but often frustrate learners because they are too complex or too sophisticated (Hegarty et al., 1999). To enable students to benefit from models, simulations, and visualizations, designers guide interactions and seek ways to promote autonomy. Models, simulations, and visualizations enable learners to connect everyday, microscopic, and symbolic representations of phenomena. They can be used in virtual labs when it is impossible, dangerous, difficult, expensive, or unethical (in the case of animal studies) to conduct a hands-on experiment. They can illustrate many fields, such as finance, mathematics, physics, meteorology, biology, social sciences, etc. Shternberg and Yerushalmy (2002) distinguish between models, that illustrate concepts (such as the relationship between a function and its derivative), and models of physical phenomena such as chemical reactions. In both types, students need strategies for exploring how the model behaves under varied conditions. Many computer-based models allow learners to explore the effect of each variable in a system by holding others constant. Oftentimes instructional materials help learners internalize the strategies appropriate for exploring complex models and simulations. For instance, students need skill in identifying extreme situations and exploring limitations of models. Students also need to connect computer simulations to hands-on experiments. Ways to guide students to explore inquiry strategies for models and simulations are exemplified in the following features.

Models of molecules in Molecular Workbench. The Molecular Workbench software allows designers to create dynamic visualizations to illustrate scientific ideas (Pallant & Tinker, 2004). Students can manipulate visualizations that link atomic level models with observable phenomena to conceptualize events like the production of greenhouse gases. An understanding of atomic level interactions is essential to most of modern science. The idea that many macroscopic phenomena emerge from large numbers of simple interactions is both simple and profound. For instance, the example model in Figure 12.10, enables students to view how their manipulation of the temperature and the mole fraction of different substances changes the speed of movement of the particles, and the reactions between them. To promote autonomy, molecular workbench visualizations have an intuitive interface. Typical students using molecular workbench demonstrate large gains in understanding of atomic and molecular level interactions, reasoning about atoms and molecules, and transfer to understanding of new problems (http://www.concord.org).

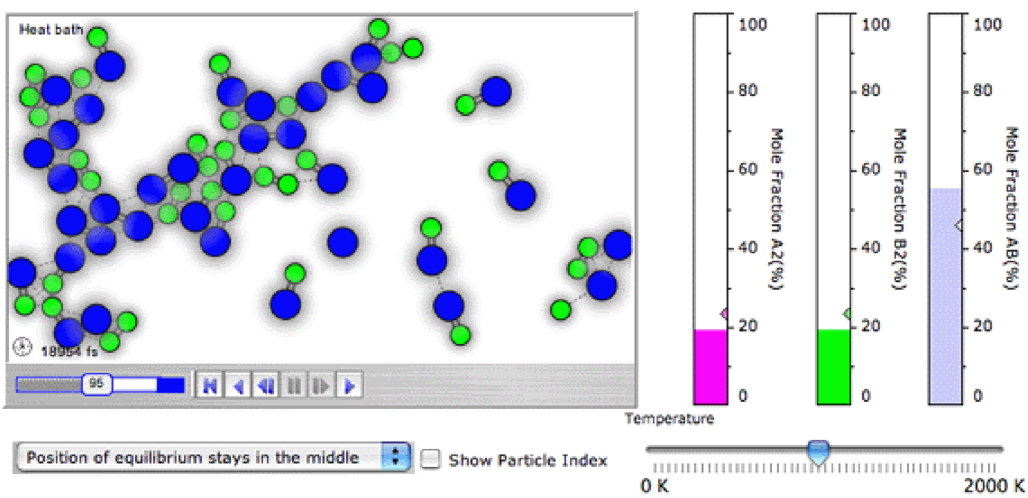

Figure 12.10: Model for exploring reversible chemical reaction designed with Molecular Workbench.

Modeling derivatives. To enable students develop a qualitative understanding of the relationship between a function and its derivative, even before they are taught the formality of mathematics, Shternberg and Yerushalmy (2002) have developed the function and derivative model (Figure 12.11), as part of the Visual Math project (http://www.cet.ac.il/math/function/english/). The model allows comparison of two views; a function view at the top, and a derivative view at the bottom. Using a set of seven graphical icons, learners can build their own function. As they build and manipulate the function, they view how the derivative changes. This model can be used for student-initiated problems or as part of the activities in the Visual Math curriculum.

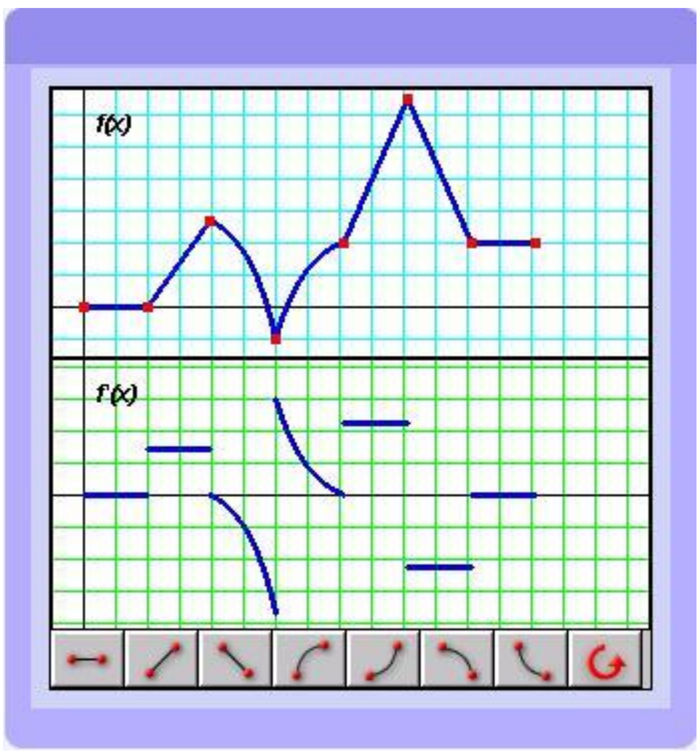

Figure 12.11: Function and derivative model in Visual Math.

12.2.4.2 Pragmatic principle: Encourage reflection

A well-established method for promoting lifelong learning is to encourage learners to reflect on their own learning and generate explanations. Linn and Hsi (2000) found that when learners reflect, they monitor their progress and reach new insights. The pattern of conducting an exploration and then reflecting improves understanding (Davis, 1998). Combining an experiment, investigation, or research endeavor with reflection can improve both activities. In contrast to text materials, technology-enhanced materials can prompt students to reflect and capture student ideas while they are learning.

Finding the appropriate amount and type of reflection requires iterative design and depends heavily on the context. Designing prompts that elicit reflection is challenging. Some prompts just lead students to conclude that they were successful (Davis & Linn, 2000). The examples below show how this principle helps teachers and learners.

Prompts for reflection-on-action in CASES. Prompts for reflection are a part of a teachers' online journal tool in CASES (Davis, 2006). They appear as sentence starters or questions listed on the left side of the journal. Two to six prompts are listed under each of three different categories: "thinking about today", "planning ahead" and "general thoughts". A teacher selects a prompt from the left column and the prompts appear in the journal. The prompts are designed to elicit information that may otherwise remain tacit, such as justifications for curricular decisions. This reflection-on-action influences student learning outcomes by helping teachers to think critically about their lessons and teaching methods, and make more effective decisions in real time in the classroom (Davis & Krajcik, 2005).

Note-taking in WISE. The WISE environment allows designers to embed notes and enables students to view them at any time. Prompts direct students to explain their ideas, make connections, or make predictions (Figure 1) Slotta (2004) shows that reflection notes can help students monitor their own learning.

12.3 DISCUSSION AND CONCLUSIONS

In summary, to identify promising supports for inquiry learning we took advantage of a community resource—the Design Principles Database. We organized the discussion around the meta-principles to capture essential elements of effective instruction. To illustrate the meta-principles, we selected the pragmatic principles that connected to the largest number of features. We provided evidence for the pragmatic principles by describing research on illustrative features. These features communicate the complexity of inquiry instruction as well as the insights emerging in recent research programs.

These results, other findings in the Design Principles Database, and related research, all provide strong support for the four meta-principles. First, effective supports for inquiry make science accessible by connecting to the interests or ideas held by the learner (Linn & Hsi, 2000; Krajcik et al., 1998). When students grapple with everyday examples, they can evaluate their intuitive ideas and distinguish them from normative views. Second, effective supports make thinking about scientific phenomena visible to teachers and learners by animating, visualizing, articulating, or representing complex phenomena in multiple ways (Linn, Lee, Tinker, Husic, & Chiu, 2006). Modern technologies offer a window on unseen scientific phenomena, combined with supports that enable interpretation of these events. Third, effective supports help students learn from each other by asking students to explain their ideas and to critique the ideas of others (Davis, 2005). When students discuss their ideas, they can develop criteria to distinguish them. Fourth, effective supports promote autonomy by stimulating learners to monitor their progress and reflect on their learning (White & Frederiksen, 1998). When students evaluate their own ideas, they can learn to think critically about their progress.

As these examples reveal, designers of inquiry environments have created powerful features that can give new designers a head start on building effective inquiry instruction. The value of the full set of meta-principles is also reflected in the connections among the features in the Design Principles Database and in the characteristics of learning environments that include multiple features. Features are linked to the pragmatic-principle that they illustrate but some features also have elements that connect to other pragmatic-principles. For example, the features that enable 3D manipulation of scientific phenomena also have elements that promote autonomy by asking students to reflect on their observations. Learning environments such as WISE and Model-it typically include features that connect to all four meta-principles. For example, WISE includes SenseMaker, Principle maker, on-line discussions, and reflection notes. Evidence in the Design Principles Database suggests that it is reasonable to conclude that effective supports for inquiry should take advantage of all four meta-principles.

Another way to evaluate the features is to examine how they support the process of knowledge integration described in the introduction. The features in the Design Principles Database support one or more of the four processes of knowledge integration: eliciting ideas, adding ideas, developing criteria, and sorting out ideas. Features such as collaborative brainstorming or reflections on everyday phenomena elicit student ideas. Features such as representations or animations of scientific phenomena add new ideas to those held by the learner. Features such as peer-evaluation or SenseMaker encourage students to develop criteria for distinguishing among ideas. Features such as causal mapper or prompts for reflection encourage learners to sort out their ideas. These connections between features and the processes of knowledge integration prompted the development of design patterns that describe promising combinations of features (Linn, 2006; Linn & Eylon, 2006).

A design pattern is a sequence of activities followed by teachers and students in a classroom. Linn and Eylon (2006) synthesized a broad range of research on inquiry science to identify patterns that employ the four knowledge integration processes in productive ways. These four processes play out in 10 design patterns that research has shown to promote knowledge integration. For example, the pattern using modeling or simulation to enable knowledge integration starts by eliciting predictions about an observable phenomenon such as heating water. Then the pattern adds ideas using a feature like Molecular Workbench. Next, the pattern might guide learners to form conjectures and compare them using a feature like Principle Maker. Finally, the pattern might help learners consolidate ideas with a feature like note taking. We are currently linking design principles and design patterns.

The Design Principles Database is effective when it is built into a structured design process, and used in a social context, such as a graduate course, or a workshop (Kali, Ronen-Fuhrmann & Hoadley, 2006). Participants in such courses found that the design principles approach assisted them in brainstorming ideas for activities, in generating alternatives and in designing specific activities. However, they found that the Design Principles Database did not provide sufficient guidance for putting these activities together to create learning environments.

Design patterns can help with this dilemma by suggesting sequences of activities. The Design Principles Database helps when designers seek ways to implement the activities in the sequence. By testing and refining these resources for designers and by adding additional resources that capture the experiences of designers, the field can become more cumulative.

The Design Principles Database is a work in progress. As more designers add their features, new pragmatic principles may emerge and existing principles may need revisions. The Design Principles Database can help the field become more cumulative by capturing the interplay between the learning context and the design guidelines. Many instructional designers use the ADDIE (Analyze, Design, Develop, Implement and Evaluate) framework to create and test innovations (Dick, Carey, & Carrey, 2001). Those committed to design research acknowledge the importance of the iterative refinement process, in which designs are tested multiple times (Barab & Squire, 2004; Bell et al., 2004; Collins et al., 2004; Design Based Research Collective, 2003). Both approaches yield results that can be added to the database. In addition, we continue to sponsor opportunities to add and refine features and principles. These activities will elaborate and improve our understanding of supports for inquiry learning.

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