Designing Technology to Support Reflection

□ Xiaodong Lin
Cindy Hmelo
Charles K. Kinzer
Teresa J. Secules

Technology can play a powerful role in supporting student reflection. Sociocognitive theories provide a conceptual framework that we use to consider systems that afford reflective thinking. Reflective thinking involves actively monitoring, evaluating, and modifying one's thinking and comparing it to both expert models and peers. This requires a combination of both individual and collaborative reflection. These theoretical frameworks suggest four ways that technology can provide powerful scaffolding for reflection: (a) process displays, (b) process prompts, (c) process models, and (d) a forum for reflective social discourse. Each approach is presented with specific examples illustrating its design features. We argue that a systems approach that combines these different scaffolding techniques may be even more powerful. Modern technologies can provide students with rich resources for reflection and help students develop adaptive learning expertise through reflective practice. We conclude with a discussion of design issues that should be considered in the future.

□ The explosive growth of technology, particularly the connectivity of the World Wide Web, requires new kinds of knowledge and learning skills. In any setting, students must not only learn how to use resources to find information; more importantly, they must also learn how to make sense of information, and decide which sources are useful and reliable. In order to make conscious decisions about the uses of information, students have to step back and reflect on how they actually make decisions and solve problems and how a particular set of problem-solving strategies is appropriate or might be improved. These skills are needed whether learning occurs with or without technology. Technology extends students' learning in terms of quantity and variety of information as well as speed of information retrieval. However, these benefits of technology make more salient than ever before students' critical thinking about their own learning and about how the information retrieved is related to that learning. The "basics" required for success in our increasingly changing society are no longer simply reading, writing and arithmetic, but the ability to think reflectively in order to make sense of information and to adapt learning flexibly to new situations (e.g., Bruer, 1993).

Without appropriate support, students have difficulty engaging in high-level reflective thinking (Hmelo & Lin, in press; Lin & Lehman, in press). For example, in recent conversations, middle-school history teachers told us that with the support of information technology, many of their students can efficiently find information and memorize facts; but unless appropriate scaffolds are provided, they cannot explain why that information is relevant and important to understanding a particular historical period. Nor can they identify what is difficult for them to understand or what they need to learn more about. Students' inability to recognize the limits of their own knowledge and understanding also hinders them from taking actions to remedy this situation. To combat these problems, it is important for students to develop the skills necessary to think reflectively and critically.

The ability to reflect upon and oversee one's own state of understanding is closely tied to flexible thinking and problem solving (Bransford & Stein, 1993; Hatano & Inagaki, 1992; Salomon & Perkins, 1989; Wineburg, in press). This notion of flexibility and adaptability has led theorists to argue that there are two levels of expertise: adaptive expertise and routine expertise. According to Hatano and Inagaki (1986), people who possess adaptive expertise frequently construct and enrich their conceptual knowledge of procedural skills, systematically reflect on the effects of actions on outcomes, and constantly attempt to improve themselves. In contrast, people with routine expertise excel in speed, accuracy and automaticity of performance, but lack the ability to reflect and flexibility to adapt to new problems. Consequently, they repeat applications with little variation and modification. Hatano & Inagaki (1992) further illustrate the concept of adaptive expertise by contrasting two types of cooking experts: (a) one could cook accurately and efficiently following fixed recipes; (b) the other was highly flexible and able to cook equally delicious dishes even with missing ingredients. Similar findings were observed in information system design and history (Miller, 1978; Wineburg, in press).

People who are able to learn and adapt are those who frequently reflect on the quality of their understanding and seek to go beyond what they know (Bransford & Nitsch, 1978). This ability is also known as metacognitive thinking (Brown, Bransford, Ferrara, & Campione, 1983; Flavell, 1987). Metacognition is an important component for success in learning new domains, solving problems, effectively utilizing prior knowledge, and organizing information and resources (Bransford & Stein, 1993; Brown et al., 1983; Scardamalia & Bereiter, 1991). A major challenge for educational technologists, then, is to go beyond simply providing students with technology tools to search efficiently for information. We must also provide scaffolds that enhance critical thinking and reflection about that information.

In brief, the thesis of this paper is that technology, properly designed and used, enables us to realize reflective learning environments that were not previously possible. We identify how technology can be designed to support reflection, and we discuss implications for future design of reflective learning environments. We do this first by discussing a socio-cultural framework for examining reflection, then by considering how technology can be used to support reflective thinking, and finally by proposing design implications for creating technological learning environments that support reflective practice.

A SOCIO-CULTURAL FRAMEWORK FOR VIEWING REFLECTION

There have been two major waves of the "cognitive revolution." DeCorte, Greer and Verschaffel (1996) note that the first wave consisted primarily of analyses of individual thinkers and learners, with a de-emphasis on affect, context, culture and history. With the second wave there have been attempts to relocate cognitive functioning within its social, cultural, and historical contexts (e.g., Brown, Collins, & Duguid, 1989). In this latter view, individual and socially-mediated reflection are complementary and both are important for helping students learn to reflect.

The extent to which learning is individually constructed is a major source of controversy in the cognitive science community (Bereiter, 1994; Cobb, 1994). Cognitive constructivists emphasize individual perspectives of knowledge construction and heterogeneity in the community (Cobb, 1994). Alternatively, socio-cultural theorists usually give priority to the social and cultural processes related to the individual's experiences. Vygotsky (1978) emphasized the social roots of cognition and the importance of the "zone of proximal development" in which interaction with knowledgeable peers plays an essential role. Moreover, socio-cultural theorists tend to look at communities as homogeneous units (Cobb, 1994). This view is further illustrated by Rogoff (1990), who states, "From the social-historical perspective, the basic unit of analysis is no longer the individual, but the social-cultural activity, involving active participation of people in socially constituted practice" (p. 14).

In synthesizing both constructivist and socio-cultural theoretical perspectives, Cobb (1994) argues that "Each of the two perspectives, the social-cultural and the constructivist, tells half of a good story, and each can be used to complement the other" (p. 17). According to Cobb (1994), the important point is "to consider what various perspectives might have to offer relative to the problems or issues at hand" (p. 18). Or as Bereiter states, there is no need to claim that one view is better than the other, and we should feel free to choose or "to mix-and-match" in whatever way gains us an advantage in solving problems (Bereiter, 1994, p. 21). This view is also shared by many other theorists and researchers (Cognition & Technology Group at Vanderbilt [CTGV], 1996).

The important point is that social constructivists believe that knowledge construction is a shared experience and is developed "by the dialectical interplay of many minds, not just one mind" (Goodman, 1986, p. 87) That is, the knowledge is constructed "when individuals engage socially in talk and activity about shared problems or tasks" (Driver, Asoko, Leach, Martimer, & Scott, 1994, p. 7). The educational goal for social constructivists is to create social environments that encourage students to construct their own understanding (Brown et al., 1989).

An Illustration of Social Constructive Theory

Examples of applying a social constructivist framework to the design and implementation of educational systems are provided by Bielaczyc and Collins (in press) and Lin et al. (1995). The examples illustrate how the concept of a learning community can help students develop abilities to reason about learning and to think reflectively, to think critically, and to become motivated to learn independently throughout their lives. Students are provided with opportunities to organize and choose their own learning and to monitor and evaluate their performance while comparing it to others' performance and thinking (Collins, 1996). In addition, learning communities often emphasize the importance of distributed expertise (e.g., Brown et al., 1993; Pea, 1993). Distributed expertise refers to expertise that resides not only in a single individual, but also is constructed through social collaboration and artifacts (Brown et al., 1993; Pea, 1993). In learning communities, assessment is used to make thinking and learning visible to the individual and to others. Assessments are viewed as opportunities for students to reflect on content as well as on their learning strategies. Assessments also enable students to determine ways of improving their learning strategies, as necessary.

A more specific example is from the Fostering Communities of Learners (FCL) project developed by a team at the University of California at Berkley (Brown et al., 1993; Brown & Campione, 1994). FCL researchers and developers emphasize that disciplines are based on sets of deep principles that students learn about through in-depth investigation of complex problems within the discipline (Brown & Campione, 1994; Sherwood, Petrosino, & Lin, 1998). FCL provides a guided discovery environment to provide structure to the students' explorations of complex problems. For example, in a unit on biology students are first given a "benchmark" lesson on a curriculum theme (e.g., endangered species). From this lesson, students generate questions; the teachers and students together categorize these questions into topics. Then students form research groups, and each group investigates one of the topics. As part of their research, students use texts, magazines, newspapers and video; they use electronic mail to consult outside experts, teachers and peers.

According to Flavell (1987), metacognitive reflection is more likely to be invoked in learning environments in which complex problems are embedded, because of increased demand for conscious decision making and questioning.

Reflection is a major component of the FCL environment. For example, when reading articles that are relevant to their research, students engage in reciprocal teaching, which organizes their reflection about what they understand and what they do not understand (see Palinscar & Brown, 1984). In addition, after different groups develop expertise in particular areas, they redistribute themselves to form "jigsaw" groups, with one student from each expert group in each jigsaw group. In the jigsaw context, peers help individual student experts reflect on their attempts to communicate their understanding as the peers try to learn from the experts. This leads to much clearer writing and understanding on the part of everyone involved (e.g., Brown & Campione, 1994).

In summary, social constructivist theory has many important implications for understanding the processes involved in reflective thinking and designing technology-based environments that support reflection.

First, reflective thinking involves social interactions because one needs multiple perspectives and feedback on one's own performance and understanding (Schwartz, Brophy, Lin, & Bransford, 1999). Often, reflection occurs when one's learning is compared and contrasted to others (Collins, 1991; Dewey, 1933; Schön, 1990). The process of reflective thinking should therefore be understood as a combination of both individual and social construction (Cobb, Boufi, McClain, & Whitenack, 1994; Collins, 1991). Furthermore, this combination may enrich individual reflection because interacting with others' perspectives may lead to renewed ways of thinking and talking about one's own learning (Collins, 1991).

Second, reflective thinking is an active, intentional, and purposeful process of exploration, discovery, and learning. It requires critical thinking and usually occurs when problems or situations encountered are perplexing, complex, and meaningful or genuine to people (Dewey, 1933; Flavell, 1987). It involves taking a mindful stance in considering how knowledge was used in the past and when it might be useful in the future (Salomon & Perkins, 1989).

Third, reflective thinking ultimately involves understanding one's own process of learning. It involves experiencing understanding of oneself as a learner in a variety of contexts; organizing, monitoring, and evaluating one's learning to derive a renewed state of understanding about one's performance (Schön, 1990).

These three aspects of reflection can all be enhanced efficiently through the use of technology. But this will only happen if these principles are built into the design of a system on the "front end." In fact, as we argue later, technology can often ensure that scaffolds to enhance reflection occur as a value-added item to other aspects of learning, and can do so in ways that are difficult in more traditional learning environments. For example, guided prompts, both in random and fixed presentation schedules, are necessary parts of making any process intentional and overt. Teachers in class discussions may forget or not prompt appropriately, but appropriately designed technology environments can ensure that advance organizers or embedded prompts appear as needed. In the next section, we will examine specific examples of systems that have, to various degrees, implemented designs to maximize scaffolds for reflection.

TECHNOLOGY DESIGN FEATURES THAT SUPPORT REFLECTIVE THINKING

Computer technologies available today were hard to imagine even 10 years ago. The new developments in technologies provide learning opportunities that were not possible with books, blackboards, and radio. Today's technologies make it possible for students to learn by solving simulated real-world problems, to challenge each other's ideas, and to display visually their own or others' problem-solving processes. In addition, Internet technologies allow students to learn through interactions with domain experts and peers from the classroom or from other countries. From our review of the literature, we identified four types of design features that provide scaffolds for reflective thinking and that can be integrated into video, the Internet, and large telecommunication systems:

1. Process displays: displaying problem-solving and thinking processes;
2. Process prompts: prompting students' atten-

tion to specific aspects of processes while learning is in action;

3. Process models: modeling of experts' thinking processes that are usually tacit so that students can compare and contrast with their own process in action;
4. Reflective social discourse: creating community-based discourse to provide multiple perspectives and feedback that can be used for reflection.

These four types of scaffolding represent effective instructional strategies that support various forms of reflection in subject domains such as reading, writing, biology, and mathematics (King, 1991; Lin & Lehman, in press; Palincsar & Brown, 1984; Scardamalia & Bereiter, 1985). Underlying these four features is the critical feature of making the learner's thinking visible. Although it is unusual to have all of the above features present in any one instructional system, the extent to which more than one appears depends on the learning goal and the type of reflection desired by the teachers and designer. Each of the above four characteristics, and their explicit nature as related to learning goals, is discussed in the sections that follow.

Process Displays

A process display shows learners explicitly what they are doing to solve a task or learn a concept. This helps make the student's own thinking and learning an object for reflection. Reflection must occur on at least two levels if it is to be a springboard to self-monitoring, self-correction, or self-motivation in learning: (a) reflection on a product and its value, and (b) reflection on the process by which the product was created. Since the product is generally explicit (consider, e.g., a piece of writing, where the product is visible and tangible), reflection on product is usually better conceptualized and implemented than reflection on process (Lin & Lehman, in press). Processes are hidden. They result in a product but are often automatic and thus not consciously accessible, or they are fleeting and are not easily captured for analysis. Consider that the process of creating a piece of writing is much harder to capture or revisit than is the written product. Reflection on the difficult-to-track processes does not occur well or easily in traditional learning settings, which focus on products.

To reflect on a process, one must step back and become consciously aware of the process being used. In traditional settings, reflection on process has been attempted through the use of support structures such as study guides and advance organizers. These, however, are easily ignored and do not always occur at appropriate times—when the learner is at a logical place (perhaps a meaning-boundary in a piece of writing) where reflection would optimally occur (Lin & Lehman, in press). On the other hand, appropriate design of technological tools can capture or record a learner's actions as they occur and play them back, either at the learner's request or in response to actions by the learner as monitored by the system.

By *process display* we mean technology that makes normally tacit learning processes explicit and overt. It is the learners' ability to see what is being done, as well as how and why it is being done, that has the potential to develop their independent metacognitive strategies. In effect, technology can facilitate reflection on what and how learning is occurring. It is this reflection—learners' explanations of why and how they performed certain procedures—that allows them to refine and enhance future process tasks. In short, our use of process display involves the use of technology not only to show students' work, but also to show how their processes led to their finished products.

A variety of computer programs have been developed to display learning processes. Most of these programs are either content-specific embedded-inquiry environments with display functions built in to support reflection (Anderson, Boyle, & Yost, 1985; Bell, 1997; Schauble, Raghavan, & Glaser, 1993) or more open-ended and content-neutral environments that students and teachers can adapt into their own domain inquiries (Brown, 1985; Loh et al., 1997). Embedded in both types of programs are ways of tracing, recording, and visually displaying students' thought and action paths. This allows students to observe their own problem-solving processes, analyze patterns, and evaluate the effectiveness of their learning. For example, Geometry Tutor, an early version of a tutorial program developed by Anderson and his colleagues (Anderson et al., 1985) was designed to help students learn geometry. The program displayed geometric reasoning processes by including student-inspectable tree diagrams of their own solution paths as students moved between the "given" and "goal" state of problem-solving. These diagrams were effective for displaying a search through well-structured problem spaces (Schauble et al., 1993).

However, when problems are complex and ill structured, simply mirroring solution paths is not sufficient. Students need to observe and analyze the complexity of their own reasoning and behaviors from multiple perspectives in order to develop deeper understanding about their own thinking and behaviors (Schauble et al., 1993). Viewing their own learning from multiple perspectives helps students notice new aspects of their thinking that they might have overlooked otherwise (Bransford, Franks, Vye, & Sherwood, 1989).

Using computers for complex displays is demonstrated by the Discovery and Reflection Notation (DARN) system developed by Schauble and her colleagues (Schauble et al., 1993). DARN provides software artifacts that show students a visual representation of their inquiry processes from multiple perspectives. An interactive, computer-generated track graphically displays students' on-line science experimentation activities. This consists of three major components: STUDENT VIEWS allows students to observe, evaluate and reflect on the patterns of experiments they have generated and to check for systematicity as they change variables, make predictions, and record data. PLAN VIEWS assists students in reflecting on the plans they made at various stages of experimentation, depicting whether experimentation activity is consistent or inconsistent with the generated plan. These views help students observe and analyze their persistence on a given path, and the relevance of their search to the goals of the experiment. EXPERT VIEWS allows students access to what an expert might say about their performance so that the students can modify their thinking and problem-solving process accordingly (Schauble et al., 1993, p. 325).

Other examples of using computers to display processes include Progress Portfolio (Loh et al., 1997), Xlibris (Schilit, Golovchinsky, & Price, 1998), Sherlock (Lesgold, Lajoie, Bunzo, & Eggan, 1992) and Heron (Reusser, 1993). Some of these tools are not content specific themselves, but they are always used in conjunction with either classroom or computer-supported learning environments designed for complex domain-specific inquiries.

The Progress Portfolio program is an example of a software application that is not content specific. The Progress Portfolio provides tools for students to create a record of their inquiry process by capturing snapshots of their work from other learning environments onto pages in the Progress Portfolio. Using notes, text fields, and graphic elements, students can record their thinking, questions, experimentation processes, and reflections around these snapshots. As students accumulate pages through their investigations, these captured pages represent a tangible trace of their progress through an investigation. Students can then organize these pages into clusters (either chronologically or thematically) and search or review them later. Finally, students can create a slide presentation out of their collected pages.

The Progress Portfolio encourages students to reflect in three ways. First, the act of having to document their work in other learning environments is reflective. Students must periodically pause in their work and make a record of their activities in the Progress Portfolio. Second, the pages in the Progress Portfolio can be customized to display specific aspects of student processes through the use of carefully designed process displaying and prompting. For example, as students work through an investigation, they might capture a specific stage of their own processes and be prompted on the same page to reflect on, "What kinds of explanations does this evidence support?" and "What evidence might lead you to disconfirm this?" Finally, creating a presentation is also a reflective act. In constructing a presentation, students must review their list of captured pages and reflect on the process of their investigation in order to decide how best to convey their argument. In reviewing the process displayed throughout the inquiry, students reassess their thinking around the captured artifacts, revisiting and revising their conclusions, and identifying gaps and mistakes.

Process Prompting

Another way to support reflection is to prompt students to explain and evaluate what they do before, during or after problem-solving acts. Whereas process display reflects back to students the process they have engaged in as tracked and analyzed by the program, we define *process prompting* as designs in which the technology poses appropriate questions and guides students in tracking and understanding their own process. Process prompts provide learners with a means of externalizing mental activities that are usually covert (Scardamalia & Bereiter, 1985). These prompts usually do not teach procedures and algorithms, but rather guide students' attention to specific aspects of their learning process (Rosenshine, Meister, & Chapman, 1996). Questions prompt students to articulate the steps they have taken and decisions they have made, facilitating their understanding of the reasons behind actions. This may lead to conceptualization of actions in powerful ways (Lin & Bielaczyc, 1998). Process prompts are especially important for those learners who tend to jump immediately into finding solutions when faced with the task of solving complex problems. If one answer does not work, they look for another with little thought about what was wrong with their first attempt. Process prompts help such learners organize, monitor, and evaluate their own problem-solving processes while learning.

Computer programs with process prompting features have used various forms of questions to engage students in explaining aspects of their inquiry processes. Students may be asked to explain content-specific knowledge, such as "what relationships have you observed between ______"; or to explain why and how specific decisions are made and their relevance to the nature of the task at hand. Prompts are usually developed based on studies of questions generated by experts in similar problem situations (e.g., King, 1991). Some process prompts are used in the context of domain-specific problem solving where the problem is represented in the software itself (e.g., Hmelo & Day, in press; Lin & Lehman, in press; Tabak & Reiser, 1997). Other prompts are generated by the instructors and students through on-line collaborative learning activities (e.g., Bell, 1997; Guzdial, Turns, Rappin, & Carlson, 1995; Scardamalia & Bereiter, 1996). These peer-generated prompts are usually used in discussion environments that are more open-ended, with the problems outside the prompting environment. In addition, prompts are also used to engage students in self-assessment of their own learning and understanding after completing a task (e.g., White & Frederiksen, 1998).

Content-specific process prompts that address problem solving can be illustrated by a computer program called BGuILE (Biology Guided Inquiry Learning Environment), developed to facilitate student-directed inquiry in high-school biology classes (Tabak & Reiser, 1997). In this environment, students conduct experiments to explain changes in finch populations. Students may take quantitative measurements of the birds' distribution and of various environmental factors. They can also examine field notes about the environment, with data represented graphically or in text form. The program includes data generation as well as interpretation, organization, categorization, and domain-specific strategic support. At various places within the program, a question-based prompting interface allows students to select a question type relevant to their specific task or to construct their own questions using question-stems provided in the program. The prompts are used to foster scientific ways of examining and explaining natural phenomena.

Another example of the use of process prompts is provided by the Isopod Simulation program (Lin & Lehman, in press). This program is designed to encourage students to explain their thought processes and actions while exploring how isopods' behaviors are affected by light, moisture, and temperature in a computer-supported simulation program. Students are prompted to reflect on their processes as they plan, design isopod experiments, set up laboratories for experiments, and collect and interpret data. These prompts include: "What more do you need to know in order to solve the problem, how do you plan on going about it, and why do you think that your conclusions are valid?" The prompts are used to encourage students to explain why, how, and what specific decisions are made. In addition, a variety of other resources are provided in the program: STRATEGY ADVISOR, DICTIONARY, REVIEWS of Lecture Sessions, HELP options, MATERIALS SUPPLY, and a LABORATORY. Students can select materials from a simulated supply cabinet to design their experiments. They then set up their experiments. At this point, they receive a prompt that asks them "Why did you set up your design this way?" They explain reasons for their designs and go on with the experiment (see Figure 1 for an example). Rather than relying on the system to provide immediate performance feedback, students are prompted to self-assess their experiments to determine for themselves the validity of their conclusions as well as why and how they came to those conclusions. Prompts that ask students to explain their decision-making and problem-solving strategies provide them with opportunities to organize and understand their own thoughts rather than just engage in problem-solving acts. This allows students to be reflective while engaged in problem solving.

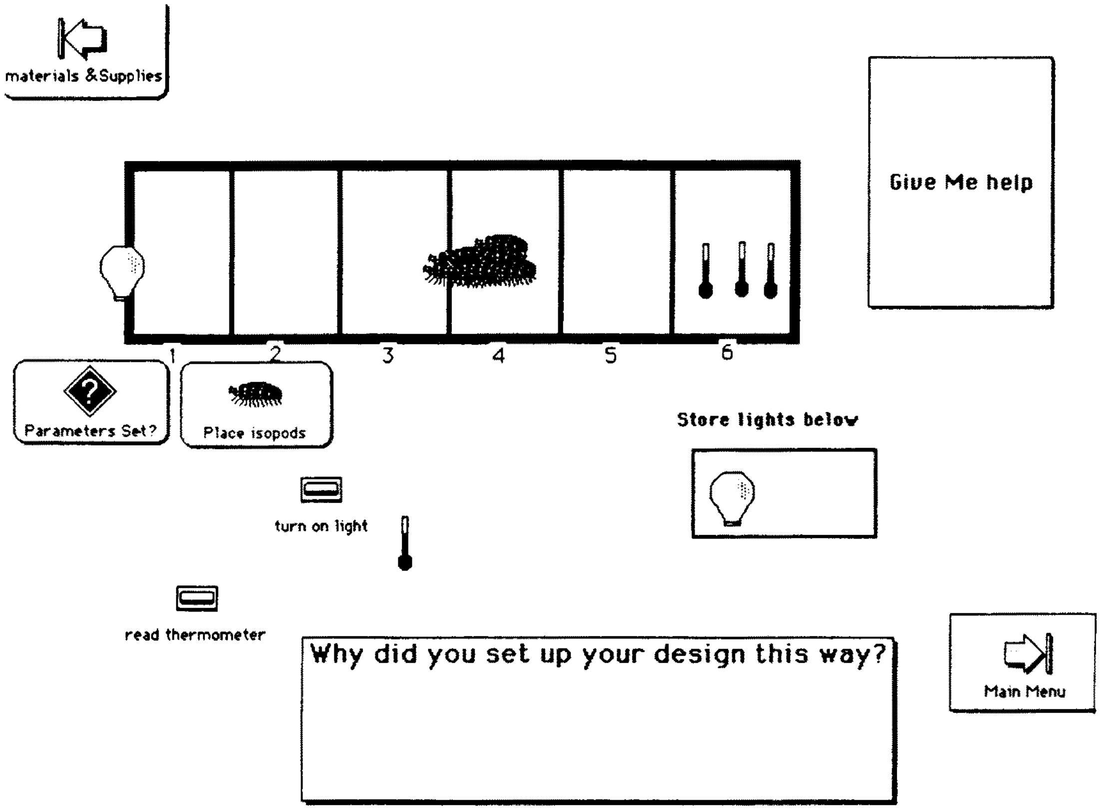
Other ways that computer programs have used process prompts to aid students' reflection include prompts triggered by student errors in a one-on-one tutoring environment such as CIRCSIM-Tutor (Hume, Michael, Rovick, & Evens, 1996); prompts providing stems to help students generate their own questions relevant to the content specific tasks at hand (King, 1991); prompts for students to assess their work against given criteria after having completed running simulations of physics experiments, as in Thinker Tools (White & Frederiksen, 1998); and prompts that the teacher can generate and sequence over a semester to target specific writing tasks using built-in teacher interface (Kirkpatrik, Stern, & Linn, 1993).

Process Modeling

In contrast to process display and process prompts, which focus on a student's process, *process modeling* focuses on the process that an expert would use in order to think about or solve specific problems. The expert's process is then used as a model for novice students who are learning about the same domain. Process modeling shows how a specific process unfolds and explains why the process occurs as shown (Collins, 1991). It is this showing and telling that is the main characteristic of process modeling (Collins, 1991). Process modeling allows students to build an integrated understanding of processes by seeing what is happening while hearing a verbal explanation of why the process is occurring. The concept of process modeling is strongly related to cognitive apprenticeship pedagogy, which uses the paradigm of situated modeling, coaching, and fading (Collins, 1991). For example, teachers who use cognitive apprenticeship models will first make their tacit knowledge and processes explicit to students by modeling their uses of strategies in a learning activity. Then the teachers provide various supports to students as they attempt similar tasks. Finally, the teachers fade their support as students continue transfer tasks independently. Similarly, in process modeling, technology models and makes explicit the thought processes underlying experts' reasoning and performance in different domains.

Technology, as discussed in the following examples, can be used to track, replay, and analyze experts' thinking processes. The use of technology to model and explain the reflective thinking processes engaged in by experts is illustrated by a video that helps students use metacognitive and self-explanation strategies in learning list processing (LISP) programming (Bielaczyc, Pirolli, & Brown, 1995). The video shows how a LISP programming expert solves particular problems, then reflects upon and revises those solutions. Students watch how the expert uses these metacognitive and self-explanation strategies while learning LISP instructional materials. The metacognitive strategies help students monitor comprehension and learning activities, clarify questions, and address comprehension failures. The self-explanation strategies help students identify and elaborate the relations between the main ideas, determine both the form and meaning of the LISP code, and connect the concepts in the texts

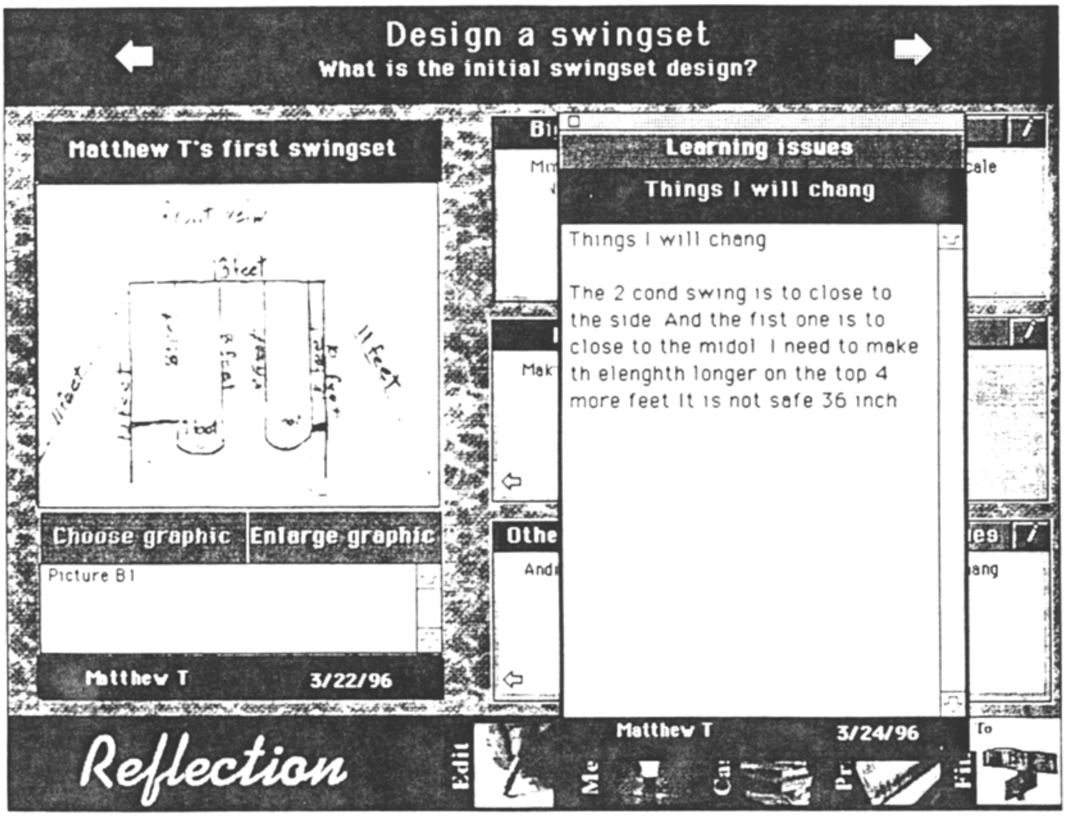
Figure 1 ☐ Isopod Simulation Program



and the examples (Bielaczyc et al., 1995). Students watch the model thinking aloud while employing self-explanation and self-regulation strategies and also watch monitoring, reflecting upon, and revising strategies as learning progresses. Students are given VCR controls and instructed to watch the video, comment on the strategies used by the model in the video, and identify strategies that seemed to be effective. Then the students apply these identified strategies in their own learning processes and reflect on the effectiveness of the strategies in their own situation. An important finding is that simply watching the video is not as effective as participating in the cycle of watching, commenting, reflecting on the processes that were modeled, practicing, and reflecting on the students' own processes (Bielaczyc et al., 1995).

Another example of process modeling comes from the ASK Jasper computer-based learning environment (Williams, Bareiss, & Reiser, 1996), which includes a performance support system to help students learn to reflect on their own products. In ASK Jasper, students learn about mathematical problem solving and basic geometry concepts in the context of designing a swing set. They begin by entering plans and drawings of their proposed swing set into a hypermedia database (see Figure 2). Structured prompts encourage students to reflect on their designs and annotate them with procedural explanations and rationales. For each step in the design process, students can access an identical database of sample designs and read annotations by experts who reflected on and identified problems with the samples. Using the experts' annotations as models, students are prompted to reflect on their own designs and make plans for revisions. In this way, students can observe the process of reflection and then compare and contrast their own reasoning and reflection on the design process to that of the experts. In addition to structured prompts and process models for reflection, ASK Jasper provides opportuni-

Figure 2 ASK Jasper

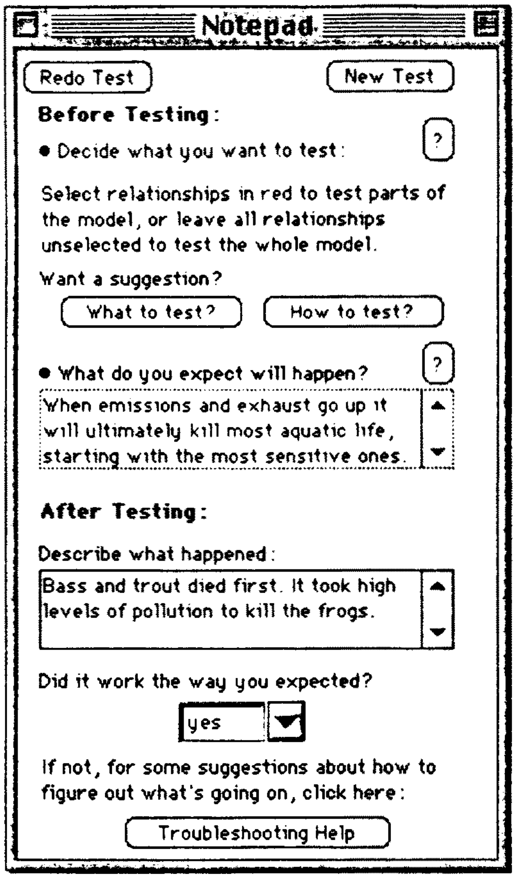


ties for students to examine each other's designs and make helpful suggestions. Teachers can use the database to examine students' work and to provide feedback during the revision process.

Model-It provides another example of technology that helps model the thinking process for learners engaged in scientific inquiry (Jackson, Krajcik, & Soloway, 1998; Jackson, Stratford, Krajcik, & Soloway, 1996). Model-It is a tool that supports project-based science by making complex systems modeling accessible to precollege students. This software has a notebook that models the kinds of questions that learners need to be asking themselves, such as "What do you expect will happen?" to encourage them to make predictions about the results of their investigations. Learners reflect by entering their plans, predictions, and evaluations into the appropriate text fields as these are relevant. This helps make the learners' goals explicit. As students work with the Model-It software, they are given prompts that refer them to the notebook and suggest that they fill in the appropriate fields. In the example shown in Figure 3, students decide to test part of a model that examines the relationship between auto emissions and aquatic life. They are asked to make a prediction, see what happens, and evaluate whether their prediction was correct. In this way, similar to ASK Jasper and the Isopod simulation, the Model-It notebook provides prompts that model appropriate thinking.

In each of the above examples, technology is designed not simply to teach specific content skills and strategies. Instead, one of the major functions of process modeling is to provide scaffolding to help students acquire deeper understanding of their own thought and problem-solving processes by comparing and contrasting themselves to expert-like models. The focus is on understanding their own thinking processes rather than on counting correct or wrong answers. In addition, students are encouraged to try the modeled processes in their own learning tasks and to reflect on their outcomes.

Figure 3 Model It



Reflective Social Discourse

The sections above have presented reflection as an individual activity. However, it is clear that reflection can also be a social activity and can be influenced by a community. For example, cooperative group work, whether in jigsaw or other approaches, requires that an individual reflects not only on his or her own efforts, but also on how those efforts relate to the group's goals. Alternatively, reflection is a social act when an individual seeks feedback from a community and modifies his or her practices based on group feedback. For example, authors circles, where peer editing conferences help an author shape a written product, exemplify social reflection. The feedback from the group sharpens and guides reflection by the author, leading to revision of what was written in ways beyond what would be possible if the individual was limited to his or her own thoughts. Reflection, therefore, while individual at one level, can also be reflective social discourse.

Over the past 10 years there have been powerful demonstrations of how computer networks can support students in engagement of reflection through community-based discourse (e.g., CTGV, 1996; Guzdial et al., 1995; Pea, 1993; Scardamalia & Bereiter, 1991). There are at least three benefits of engaging in social reflective discourse. First, network-based technologies allow people of different cultures and communities to be increasingly interactive. This brings to bear multiple perspectives and distributed expertise to support students' reflection in ways that were not previously possible. Multiple perspectives help students notice new things about themselves or others that they might otherwise overlook (Bransford et al., 1989; Schwartz et al., 1999), and makes their reasoning and thinking more visible. Second, reflection and revisions become more motivating when there are public audiences to evaluate and judge students' work and thinking (Schwartz et al., 1999). Third, most network technologies are also capable of tracing, recording, and displaying the students' thought processes, including how thoughts change through the help of others. This allows thoughts to become artifacts or objects for reflection and revision, as well as helping students appreciate and respect other people and their ideas (Lin & Bielaczyc, 1998).

Shared learning experiences through social reflective discourse have been regarded as an important aspect of reflection for some time (Bereiter, 1994; Cobb, 1994). There are many examples of communication technologies that support community-based reflection: Computer-Supported Intentional Learning Environment (CSILE); (Scardamalia and Bereiter, 1991); Global Learning and Observations to Benefit the Environment (GLOBE) (Lawless & Coppola, 1996; Means, 1997); Learning Through Collaborative Visualization (CoVis) (Pea, 1994); Kids as Global Scientists (KGS) (Songer, 1996); and Co-NECT (Bolt, Beranek, & Newman, 1994). An important characteristic of these technologies is that they were designed as a means to support reflective discourse-based approaches in the context of complex problem solving. This creates communities and scaffolds for students who are developing more personal understanding of the domain targeted by the respective program (CTGV, 1996). In addition, the programs noted above also provide "just-in-time" feedback and conceptual tools to sustain and enrich community-based reflective discourse (e.g., Barron et al., in press; CTGV, 1996).

CSILE, a specific example of communication technology, connects several computers within or across classrooms through a file server (Scardamalia and Bereiter, 1991). The file server contains a communal database, with both text and graphic capabilities. Within this networked multimedia environment students create "notes" of labeled types, containing an idea or piece of information relevant to the topic under study. Using CSILE, students discuss their questions and theories, compare and contrast different perspectives from peers, teachers, and experts, and reflect on their individual and joint understanding of a problem (see Table 1). Students can learn individually as well as collaboratively by articulating their own understanding, commenting on each other's thinking, and modifying their ideas based on their engagement in classroom activities or in the communal database. The database allows students to reflect on their own learning by contrasting themselves with peers and by responding to peers' comments on their work.

The most promising aspect of the CSILE environment is that it supports learners in sustained reflective discourses about their own and others' ideas. These discourses are usually guided by a teacher. Teacher tools provide several ways to trace both the content and discourse processes students are engaged in, for both instructional and assessment purposes. Teachers can go through the paths of students' discourse to gain an understanding of the patterns of students' reflection and changes in students' thoughts. This helps guide collaborative discourse wherein participants, invested in the process of reasoning and knowledge building, engage in reflection about their own learning processes and about the community at large (Scardamalia & Bereiter, 1991).

Another example is the GLOBE project (visit http://www.globe.gov/), currently in more than 4,000 schools of more than 60 countries, which involves students and teachers working with research scientists to learn more about our planet (Lawless & Coppola, 1996; Means, 1997). GLOBE students make a core set of environmental observations at or near their schools and submit their data through the Internet into a GLOBE data archive, which is used by the scientists, teachers, and students to perform their analyses. GLOBE also provides a set of visualization tools, available on the Internet Web site, which enables students to compare and contrast their own data with data collected worldwide.

Other communication-oriented technologies include the AT&T Learning Circles (Riel, 1990) that link classes from geographically diverse locations so they can share educational and learning experiences; the Urban Math Collaborative (UMC) that links school teachers and university mathematicians in order to deepen teachers' knowledge domain (Driscoll & Kelemanik, 1991), the Collaborative Learning Laboratory that facilitates collaborative learning among members in medical education (Koschmann, Myers, Feltovich, & Barrows, 1994); and the Discourse System that facilitates interactive group-based instruction (Bennett & King, 1991). All of the examples presented in this section target social aspects of learning by facilitating group communication and reflection.

Toward a Systems Approach to Support Reflection

We have discussed four types of design features (process displays, process prompts, process models, and a forum for reflective social discourse) that support reflective thinking for which technologies provide particular leverage. Each type supports a different aspect of reflective thinking, any of which may be necessary in a complex learning situation. Optimally, we could develop programs that incorporate all four features, each at the appropriate time, given the learning goals and needs of a particular domain.

As technology becomes more sophisticated, it enables us to create environments where a combination of these four features in a single system is possible. For example, a later version of the previously mentioned Geometry Tutor included

Table 1 CSILE Notes

Problem Which character in the books we have read this year went through the greatest changes in his/her life circumstances or how he/she viewed the world? (Please make sure you also mention the title of the novel as well as the character and EXPLAIN why you selected this particular character.)

12	My Theory: They changed their life by almost dying and trying to survive. (DN)
14	My Theory: I think Brian Robeson from the novel HATCHET has gone through the greatest changes, because he got lost in the wilderness, and had to survive without anybody teaching him. (TT)
18	My Theory: My opinion is that Brian went through the most changes because he had to learn himself how to make fire, how to eat certain foods, hunt, and how to just survive the whole time. Then the plane came and took him, and saved his life Miyax, on the other hand, was taught more by her dad to survive because he was a hunter. Miyax had a few changes like eating, and getting used to partially-digested food. Derek, in the River, had changes too, but not as much. (LD)
20	My Theory: I think it's Miyax because she is lost in the Alaskan arctic snow. She is probably cold, and it is hard to find something to eat, but she is not alone. She is the adopted daughter of Amoroq [lead wolf]. (BE)
21	My Theory. I think it's Miyax, because she is the one that had the hardest time, because the plane kept passing her, sometime's. (RW)
24	Comment: David, What do you mean. It doesn't answer the question. Who went through the most changes, Miyax or Brian. (AR)
36	I Need to Know: Rod, I like what you said in a way but how could Miyax be the one that had the most changes: Brian had to learn how to make fire, hunt food, make rafts, make shelters, and other things. Miyax knew a lot of things from survival because her dad was a hunter. If she did make a lot of changes she wouldn't of already knew how to talk to animals. Plus, she probably wouldn't of knew that wolves ate the way they did. I didn't even know that. So how could Miyax make the most changes? I'm not against you, but how? (LD)
38	Comment: Brian E. I totally agree with what you said, but I want to know why you think this? (JB)
46	Comment: Brian, I like what you said, but why do you think Miyax went through the greatest changes. Brian had to survive twice and made it with another person he had to take care of READ!!! #14. (TT)
47	My Theory: I got mixed up Friday and this is what I think, I think Brian Robeson went through the greatest changes because he went from a "City Boy" to a "survivor." (DN)
50	Comment: David, MUCH BETTER! I'm glad you went back and read your first response and revised. I'm also glad you read more carefully . . . good advise from some of your classmates! (BR)
58	My Theory: Tony, It was kind of easier for Brian because he could find something to eat because he had trees and could shoot birds with an arrow. Miyax is around snow. Everywhere you look is snow, and she has to depend on the wolves for food. (BE)
59	My Theory: Lindsey, you are wrong about the hand signals her dad told her not taught her how to do it. Now here's your question I think she did, because she didn't hunt but when the wolves left her now she had to hunt.

both process display and process modeling by using visual diagram configurations not only to trace the student's own path, but also to show how expert geometricians solve a wide variety of problems. Recently, we have examined some integrative technology systems that combine all four features to support reflection. Often such systems feature a series of inquiry cycles organized around challenges derived from complex, domain-specific problems. Examples of such systems include Software Technology for Action and Reflection-Legacy (STAR.Legacy), developed by Schwartz and his colleagues (1999), ASK Jasper (Williams et al., 1996); and SenseMaker (Bell, 1997). Because these systems are similar (all provide multiple means to support reflection differing only in the program complexity and domain), we use only STAR.Legacy as an example.

A major function of STAR.Legacy is to provide a framework for guiding learning and reflection in a complex learning environment. The STAR.Legacy software shell consists of several components that form a complete learning cycle:

- LOOK AHEAD AND REFLECT BACK helps students understand the learning goals and reflect on their performance at the beginning and ending of the learning cycle. This allows students to identify specific areas in which they need to learn more by process display of their performance at an early state of learning.

- CHALLENGE brings real-world problems to the classroom; this sets up a context for learning and problem solving.
- GENERATE IDEAS provides a notebook tool for students to store their ideas for subsequent reflection.
- MULTIPLE PERSPECTIVES models how experts think and reflect, and allows students to compare their ideas with those generated by experts; this incorporates process prompting and modeling features.
- RESEARCH AND REVISE engages students in research activities that are tightly related to the challenge, including direct instruction and skill-building; this generates a need and an opportunity for reflective social discourse.
- TEST YOUR METTLE prompts students to reflect on how well they have learned and to identify areas needing improvement using the knowledge gained by revisiting their processes displayed from earlier in the Legacy cycle.
- GO PUBLIC provides students access to reflective social discussions about each other's work and allows students to leave "legacies" for future generations of learners.

Teachers and students can start or repeat any of the above learning experiences in the Legacy depending on the needs and goals of the instruction. The key is to know when and why a specific reflective activity is performed.

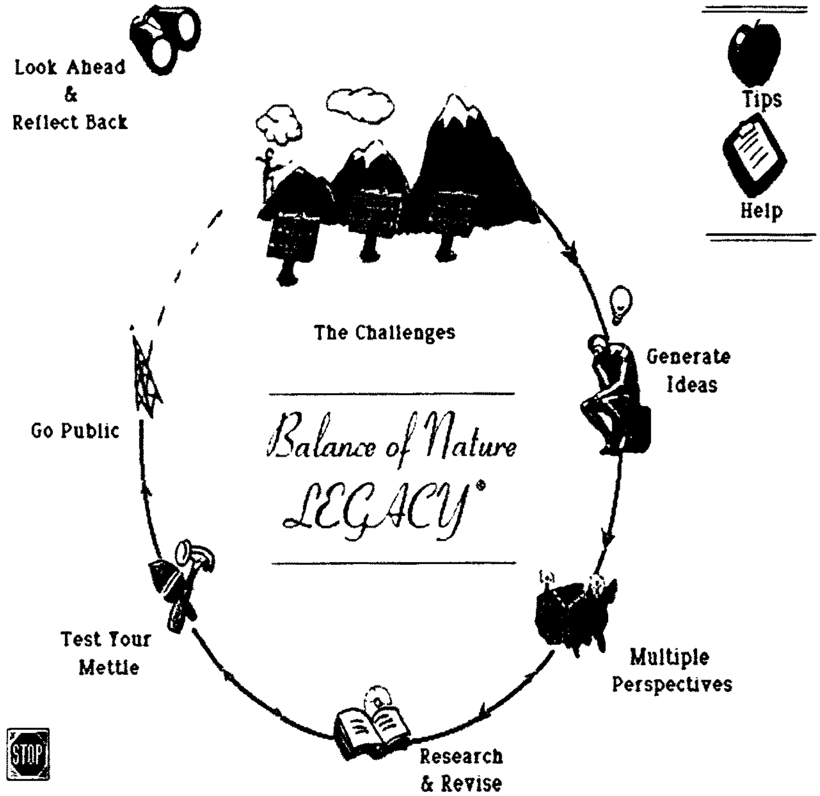
STAR.Legacy also provides a visual representation for inquiry cycles and process modeling at a global level (see Figure 4). In addition to the visual structure, STAR.Legacy provides teaching tips, including formative assessment and reflective activities, at each phase of inquiry. Designers of STAR.Legacy provide teachers with various resources and tools to engage students in reflection. These tools include hands-on activities contrasting textual resources and video segments, simple simulations, and tools that allow teachers to analyze students' learning efficiently. The software also provides support for the designers and teachers to share their reflections on pedagogical rationales for particular instructional activities and uses of resources.

Figure 4 provides an example of using Legacy, the Balance of Nature, to support students' learning about ecosystems (Schwartz et al., 1999). In the Balance of Nature students begin to explore the effect of exotic species in an ecosystem by watching a video of a young man, Chris, who presents his problem to the classroom. During his vacation in Mexico, Chris had bought a plant that a store owner said would repel mosquitoes. However, the plant had been confiscated at customs when he entered the United States. He asks students in the class to help him understand why a plant from another country cannot be brought through customs. Students in the class brainstorm and record their ideas. They then hear from experts who speculate on the following possibilities: insect or disease pests, illegal drugs, and uncontrollable exotics. These perspectives guide students' research activities. Materials and references are provided for students' research, as well as a forum for social reflective discussions on what they found out from their research. Students compare the results of their research with data collected from other students; then they revisit their research processes and the original ideas generated at the early stage of the learning cycle. They share their research results via the Internet with students from other parts of the country, and leave a message for future students about lessons they have learned from researching the Balance of Nature. Other examples of using Legacy are described in detail in Schwartz et al. (1999).

The Legacy software shell helps teachers and designers organize curriculum into learning experiences. It encourages flexibly adaptive design because it can be used to support learning and reflection in any subject domain. This very flexibility, however, makes it vital that the designers and teachers adapt Legacy instructional and reflective activities to the specific learning goals of the domain.

There are at least four important benefits to such a systems approach. First, a systems approach to reflection provides global support that helps students and teachers see why they do what they do and how their knowledge deepens throughout the learning cycle. The reflective activities are organized around a set of problems with clear learning goals, which help both teach-

Figure 4 STAR Legacy Program



ers and students keep track of where they are in the learning cycle and what more needs to be learned in order to solve the problem. Second, learning and reflection on previous actions can be applied immediately to subsequent tasks embedded in the learning cycle. This allows students to see and experience the usefulness of reflective processes in achieving learning goals instead of merely engaging in reflective acts as ends in themselves. Seeing why, how, and where reflection is needed helps students develop conditionalized knowledge about reflection, which is important for promoting transfer (Brown et al., 1983; Salomon & Perkins, 1989). Third, a systems approach enhances reflection because students' understanding of processes can be explicitly represented by technology in various ways: process displays, process prompts, process modeling and reflective social discourse. Finally, a systems approach motivates reflection by facilitating students' noticing the changes in their own learning throughout the learning cycle, especially by comparing their own knowledge at the beginning and end of the cycle. Knowing that they are making progress motivates students to reflect on how progress is being made and what must be done to continue (Schwartz et al., 1999).

IMPLICATIONS FOR DESIGN AND DEVELOPMENT

A major goal of supporting reflection is to help students fill in the gaps in their own understanding. In reviewing technology programs designed to support reflection, we have identified several design considerations shared across the different types of programs. These common characteristics have important implications for future designs. All of the programs reviewed have clear goals for reflection, with various built-in features that help students identify gaps in their understanding by displaying, prompting, modeling, communicating, or all four, about their own and other people's learning processes.

All of the programs take advantage of the leverage provided by technology to display learning processes in multiple formats, such as graphics, text, animation or audio. In addition, most of the programs embed support for reflection in complex problem-solving domains, provide students with opportunities to generate their own solutions, and help students see their processes from multiple perspectives. Furthermore, these programs have built-in research activities leading to refinements and eventual support for teachers. Using these common design considerations, we present five design questions to consider when creating technologies to support students' understanding through reflection.

Question 1: Which characteristics of reflection should be supported and included in a system and why?

Most of the programs reviewed above use technology to help students make their thinking visible and to record and abstract the problem-solving processes students use in the learning environments. However, the four basic ways to support reflection are not mutually exclusive. The challenge for designers is to decide what types of reflection should be supported for any particular learning process. Suggested answers to this question are shown in Table 2.

Knowing the learning requirements within the specific domain targeted by the respective program helps designers decide which of the above goals for reflection the program should support. For example, a recent episode of Scientists In Action (Sherwood et al., 1998) uses process modeling to show how experts sample river water for quality monitoring. Because it is important that the sampling procedures are done correctly with regard to accepted scientific procedures, expert modeling is used. However, in order to help students understand which sampling tools are appropriate at which times, process prompts are combined with expert modeling in the program's design.

Question 2: What is the role of problem complexity in design decisions?

Flavell (1987) notes that people intuitively see the need for reflection when learning situations require sophisticated decision making and reasoning. Thus, it is important to provide environments containing complex but manageable problems when the goal is facilitating the development of reflective thinking. Most of the programs we reviewed scaffold students' reflection in complex problem-solving contexts. Simple, well-structured problems can lead to learning simple facts or procedures but do not lend themselves well to enhancing decision making or reflecting on one's decisions or actions.

Question 3: Why do system designs incorporate multiple perspectives on problems?

Regardless of the type of reflection that is desired, it is important to allow students to see and experience their own learning processes from multiple perspectives, especially when it comes to dealing with ill-defined, complex problems. Individual reflection can lead students down a garden path unless it is compared to others' views. Thus, reflection, especially by novices, needs to be viewed through the lens of others' comments—perhaps those of experts—in order for students to see their own growth and insights in context. This is seen in several current systems. For example, students reflecting in the DARN program (Schauble et al., 1993)

Table 2 ☐ Goals For Reflection and Their Design Characteristics.

Goals	*Design Characteristics Incorporated*
1. Show students what process they have gone through to accomplish a particular task	1. Process display features should be incorporated
2. Call students' attention to their own processes while they are performing a particular task	2. Process prompt should be incorporated
3. Help students understand how an expert would think through and solve a similar problem or to compare their own process with those of an expert	3. Process modeling features should be incorporated
4. Provide students with multiple perspectives on content or process through focused social discourse	4. Reflective social discourse features should be incorporated

are able to see the processes of their performance from students' views, experts' views and planner's views. CSILE (Scardamalia and Bereiter, 1991) and other network technologies create a supportive community within which students can reflect and incorporate different perspectives provided by peers, teachers, experts and other members of the community. Students can evaluate the quality of their own performance by using feedback generated by other people.

Question 4: What support will teachers need to organize reflective activities and engage students in the use of the reflective design features embedded in the program?

Providing students with tools for reflection does not guarantee that they will use them appropriately, if at all. Teachers are crucial in creating classroom norms and structures that increase the value that students place on reflection. Designs that support such classrooms help teachers organize reflective activities that focus on students' understanding without losing the big picture of where the class is heading. For example, the STAR.Legacy program (Schwartz et al., 1999), provides teachers with a framework for organizing problem-based learning and concurrent reflective activities. This framework allows teachers to see visually where the class is and where the class is heading to achieve learning goals. In addition, suggestions for the use of various resources and teaching tips are also provided so that teachers can adapt these resources into their specific classroom needs.

Question 5: How can program design help teachers analyze and interpret results obtained from students' reflection?

Especially in complex problem-solving domains, it is important to provide teachers with flexible structures and tools to support their analysis and interpretation of students' processes. Further, these tools must be easy enough to use that teachers do so frequently so they can provide timely scaffolds for students' reflection and performance. Teacher knowledge of students' learning processes, and the difficulties and successes that they encounter, is critical if teachers are to provide support for their students. There is no case in the programs we reviewed in which students succeed only through the use of technology. Teachers are a vital factor; they can use information provided by technology tools to better help their students in reflection and learning. For example, CSILE has a Teacher Tool that helps teachers manage CSILE databases and provides them with a sense of the nature of the students' discourse (Cohen, 1994). The Teacher Tool allows teachers to go through the path of students' discourse to gain an understanding of the patterns of students' reflection and changes in students' thoughts. Teachers can pick a particular student or a group of students for further analysis. Such tools may have benefits beyond providing teachers with ways to help their students become more reflective. These tools can also help teachers become more reflective about their own teaching.

CONCLUSIONS

This paper has provided a structure and argument for inclusion of reflection in instructional systems as necessary to learners' growth. Scaffolding for reflection can be categorized in four ways:

1. process displays
2. process prompts
3. process models
4. reflective social discourse

Numerous examples of systems that incorporate one or more of these features were discussed. Based on the conceptual framework that we described, we propose the following design considerations to scaffold learner reflection in technology-based instructional systems:

- Match specific design characteristics to desired goals for reflection, as shown in Table 2.
- Use problems that are sufficiently complex to assure reflection.
- Use a design that builds in opportunities for learners to compare their reflection with the multiple perspectives of others.
- Use a design that provides support for teachers to organize reflective activities.
- Use a design that facilitates teachers' analysis and interpretation of the results obtained from students' reflection.

Reflection is important in preparing students to be effective lifelong learners. If people are to become adaptive thinkers, learners, and problem solvers, they must be able to think reflectively. But often students do not stop to reflect on their thinking, and teachers may not have sophisticated tools and resources to facilitate students' reflection. Technology, then, may play a powerful role in supporting individual and group reflection.

We have demonstrated four different design features for scaffolding reflection. All these features have value in supporting diverse kinds of reflective thinking; however, we do not advocate necessarily trying to incorporate all features in all systems. Rather, we argue for the importance of a systems approach to designing technology to support reflection. In other words, system designers need to incorporate the right kind of technology support at the appropriate time, considering when to support individual reflection and when collaborative reflection needs to be encouraged. In a systems approach, reflection is a means toward empowering learners, not an end in itself. The aim of teaching students to reflect on their thinking processes is to increase their awareness of their own learning, and to enable them to use that awareness to adapt their thinking in other situations. The power of technology for learning can be greatly enhanced through support for reflection, which helps learners construct the new kinds of knowledge and skills they need in this age of information. □

Xiaodong Lin is with the Department of Teaching and Learning and the Learning Technology Center, Peabody College, Vanderbilt University, Nashville.

Cindy Hmelo is with the Department of Educational Psychology at the Graduate School of Education, Rutgers University, New Brunswick, NJ.

Charles K. Kinzer is with the Department of Teaching and Learning and the Learning Technology Center, Peabody College.

Teresa J. Secules is with the Learning Technology Center, Peabody College.

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