Supporting Science Learning and Teaching with Software-based Scaffolding

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Much attention has been focused on the role of teachers and curriculum materials in scaffolding learners. However, a growing area of focus is on the potential of computer software to provide cognitive support for learners engaging in complex intellectual activities. A substantial amount of research and development in this area, particularly at the University of Michigan, has focused on scaffolding learners in science classrooms to help them develop a stronger understanding of scientific content and practice. Much of this research revolves around identifying different scaffolding approaches and developing software that implements these approaches to scaffold learners so they can engage in authentic scientific activity.

Recent research efforts have synthesized the lessons from previous scaffolding research to articulate specific scaffolding guidelines and principles that characterize scaffolding approaches at a conceptual level (e.g., Kali, in press; Linn, Bell, & Davis, 2004). For example, the Scaffolding Design Framework (Quintana *et al.*, 2004) describes a set of scaffolding guidelines, strategies, and examples that are specifically organized around the obstacles and complexities that learners face in three primary constituent aspects of science inquiry: sense making, process management, and reflection and articulation. By considering these aspects of science inquiry, the framework describes scaffolding approaches that can support learners as they attempt to engage in more authentic scientific inquiry.

Traditionally, most scaffolded software in science has attempted to support *learners*, where learners are defined as students in classrooms. But if we consider the science classroom context, the complexity introduced by inquiry-based activity also impacts the teachers in those classrooms. Therefore, there is now also a growing line of research focusing on scaffolding teachers as they develop instructional practices that revolve around an inquiry-based approach. In this paper, we will use the Scaffolding Design Framework as a basis to describe how software can scaffold students and teachers with authentic inquiry-based science activities in K-12 classrooms. We will review the framework to describe the areas where students need support in science inquiry, describe corresponding scaffolding approaches to address those needs for support, and provide examples that illustrate different scaffolding approaches from a range of software projects. (While we summarize different aspects of the framework here, Quintana et al. (2004) provide a more detailed description of the complexities in science inquiry and corresponding scaffolding approaches.) We will also extend the framework to include instances of how scaffolded software can support teachers who are developing their science teaching practices.

Theoretical Foundations for Scaffolding in Software

The development of scaffolded software emerges as an extension of traditional scaffolding descriptions in the education and psychology literature. In general, we take a socio-cognitive perspective to scaffolding that incorporates a range of ideas about supporting learners to engage in complex practices. As a theoretical basis, we use the traditional notion of scaffolding put forth by Wood, Bruner, and Ross (1975) and draw further from cognitive apprenticeship models (Collins, Brown, & Newman, 1989) and other models of cognition (e.g., Anderson, 1983) to describe the types and nature of assistance that can be provided to learners. We also consider social constructivism (Vygotsky, 1978) and situated cognition (Lave & Wenger, 1991) to further elaborate on the contextual and social aspects of learning and how they impact the timing and sources of scaffolding. These diverse theoretical ideas provide a general foundation for scaffolding that can be applied in a range of contexts. The key ideas that emerge include the identification of specific difficulties that learners encounter as they attempt to engage in a given practice, the provision of assistance to the learner by a more capable agent or agents, the potential for multiple agents in a social setting to provide different types of support to the learner, and the notion that this assistance is temporary and should "fade" away as the novice becomes more capable and no longer requires the support.

While the traditional concept of scaffolding involves support as provided by a human agent, the notion of scaffolding has also been extended to software, where the software itself acts as the more capable agent that is supporting the learner. Guzdial (1994) introduced the notion of software-realized scaffolding by illustrating how some conceptual aspects of scaffolding could be implemented in software. In particular, Guzdial focused on how software could implement different scaffolding techniques to model tasks, provide coaching, and elicit articulation. Other software projects have implemented scaffolding features informed by different perspectives on learning, from cognitive tutors to constructivist tools and learning environments. Still other projects explored the fading aspects of scaffolding by researching how scaffolding features in software might fade when no longer needed by learners (Jackson, Krajcik, & Soloway, 1998).

There is now a range of scaffolded software projects in different content areas. While there is a diversity of scaffolded software, many of these projects focus on supporting different science inquiry activities and the science inquiry process as a whole. This deep focus on science inquiry stems from the different complexities that learners encounter in inquiry-based practices. We now describe the notion of an inquiry-based approach for science and introduce the complexities that students and teachers face in those contexts.

Inquiry-based Practices and Science Classrooms

An increasingly popular pedagogical and curricular approach that has been adopted for science classrooms is based on an inquiry model. The specifics of an inquiry model may differ depending on the content area and instructional context, but we can define some general characteristics for an inquiry-based approach. For example, the National Research Council (2000) describes a general inquiry model as one where learners:

- Pose questions to investigate;
- Engage in exploratory and analytical work to gather, analyze, and synthesize information and data related to their question;
- Synthesize the results of their work to develop an explanation or answer to their question.

While this description provides a general inquiry skeleton, the specifics of a given inquiry approach can vary depending on the types of questions being posed or the content area being explored. For example, the project-based science approach (Blumenfeld *et al.*, 1991; Krajcik *et al.*, 1998), developed at Michigan, has been implemented in science classrooms where students engage in different data collection, data analysis, and modeling activities as part of their inquiry. Other instances of inquiry include an online inquiry approach where students search online resources for information that they read and analyze in order to develop their argument (e.g., Harada & Tepe, 1998; Jukes, 2000).

An inquiry-based approach can be advantageous for learners in several ways. Inquiry can provide motivating, active learning contexts situated around personally meaningful questions as a basis for more authentic scientific activity. However, inquiry can also be complex for learners due to the open-ended, iterative, ill-structured nature of the process (Quintana *et al.*, 1999). Students who have less experience in science inquiry may not know what the process entails, nor the work involved in and purpose for different inquiry activities.

Students may not understand the norms and criteria used to analyze and understand scientific material. Also, students may simply be overwhelmed by the many tasks involved in science inquiry, which prevents them from successfully completing different activities or working in a reflective manner that is conducive for learning. Furthermore, in a classroom setting, students not only have to deal with the inquiry process and inquiry activities, but they must also work with peers and teachers, who act as partners and sources of assistance, adding another level of complexity to the work.

Aside from students' need for support, teachers also need support to manage instruction in an inquiry-based classroom. Inquiry-based teaching is more demanding for teachers, both in terms of necessary content knowledge and in terms of classroom management (Crawford, 2000; Krajcik et al., 1998). Because student projects can be open-ended or go in unexpected directions, teachers require a much broader depth of content knowledge, or alternatively, knowledge of how to help guide students towards materials and information sources related to their project investigations. Compared to more traditional recitation classrooms, inquiry-oriented classrooms also introduce much more complicated activity structures that include collaboration among students, multiple kinds of simultaneous activity, and meaning-making activities. If you add technology to the mix (technology is a frequent component of inquiry-oriented science instruction in materials developed at Michigan), that adds yet another layer of complexity for teachers (Blumenfeld *et al.*, 2000). Therefore, we have also focused on teachers as learners and the entire process of teacher learning in professional development, attempting both to understand how best to support teacher learning and how to link professional development designs to classroom practice and student learning (Fishman, Marx, Best, & Tal, 2003).

Scaffolding Inquiry-based Activities in Science Classrooms

As we explore and develop scaffolded software for science classrooms, we continue to identify different scaffolding approaches that can support students and teachers through the complexities of science inquiry. We will describe these different scaffolding approaches using the organizational structure of the Scaffolding Design Framework. This framework is a useful structure because it is organized in terms of sense making, process management, and reflection and articulation. Furthermore, the framework contains a set of scaffolding guidelines and strategies that we can use to describe how different scaffolding features in software can support students and teachers with the complexities found in each inquiry component.

Scaffolding Sense Making

Learning how to make sense of and understand data and scientific information is a key and challenging component of scientific inquiry. It is through sense making activity that learners can begin developing an understanding of scientific content and craft answers to the questions that they have posed. However, since learners may lack an accurate understanding of scientific content, they face difficulty in trying to make sense of what is, for them, new material. Scaffolding sense making involves different strategies that support learners to explore data in different ways and make connections between new scientific information and their prior knowledge.

Two related scaffolding strategies that can help learners make sense of scientific data and concepts involve the composition of software interfaces. Software can be organized around the semantics of the scientific domain they are engaged in. For example, the software interface can be designed to directly reflect disciplinary concepts in the language and options that it presents to learners. Similarly, the software interface can incorporate representations and language that bridge learners' understanding by casting scientific material in terms of language and concepts that learners already have. One example can be found in Model-It, a system dynamics modeling tool for middle school and high school students (Metcalf, Krajcik, & Soloway, 2000). Students use Model-It to create models of systems, such as ecosystems or social systems. In order to create system models, students use the software to define the different objects in the system, the variables possessed by those objects, and the relationships between different variables. Typically, defining relationships in system modeling software involves developing mathematical equations to describe the relationship. Model-It restructures this task by casting relationship development in terms of "real-world" language that is more understandable to students. Figure 1 shows the Model-It relationship editor, where a student is defining a relationship between SO_2 levels in a city and asthma levels in the population. Rather than directly using mathematical equations to define the relationship, Model-It uses a qualitative approach where students build sentences using pull-down menus to define the relationship. Here, students define the relationship in the following way—"as SO_2 levels in the city increase, then asthma levels in the population increase by about the same rate". Therefore students build relationships for their model using more intuitive language that they bring to the modeling task, helping to make the modeling task more accessible.

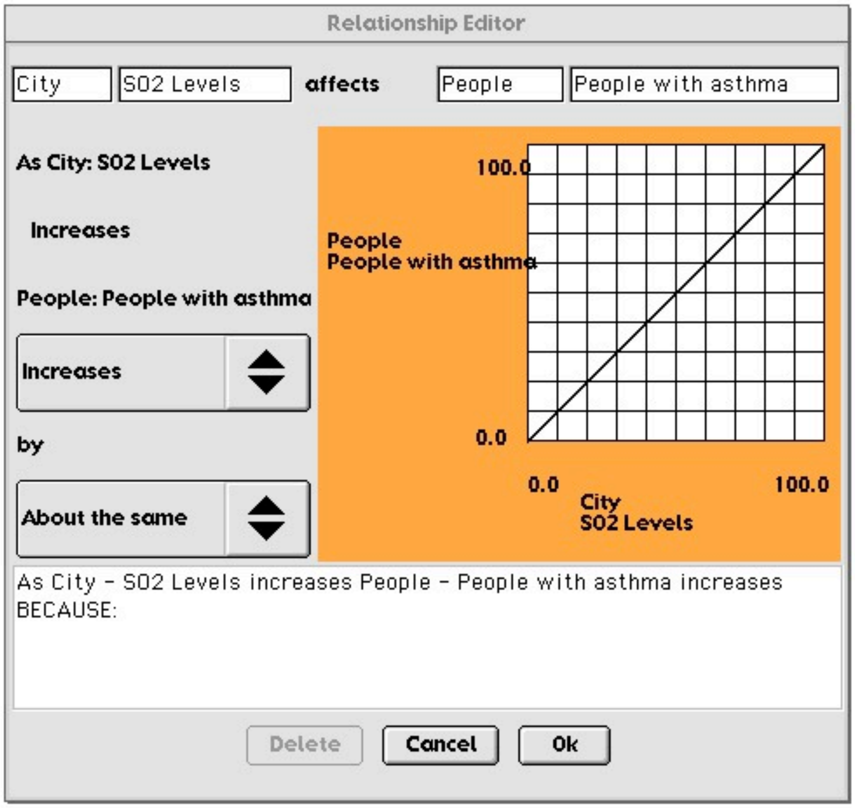

Figure 1. The Model-It Relationship Editor

Another scaffolding strategy that can be realized with software involves incorporating scientific representations that learners can inspect and manipulate in multiple ways in order to understand different characteristics and patterns in those representations. An example of this type of software-based scaffolding feature can be found in eChem, a molecular visualization program for students (Wu, Krajcik, & Soloway, 2002). In eChem, students build and explore different representations of molecules. Figure 2 shows the eChem visualization workspace, where students can see different views of the molecules that they constructed, such as the ball-and-stick and space fill views seen here. Additionally, students can manipulate the molecules by rotating them so they can explore and view molecules from different perspectives. This allows the type of exploratory activity that can help students understand different characteristics of scientific phenomena.

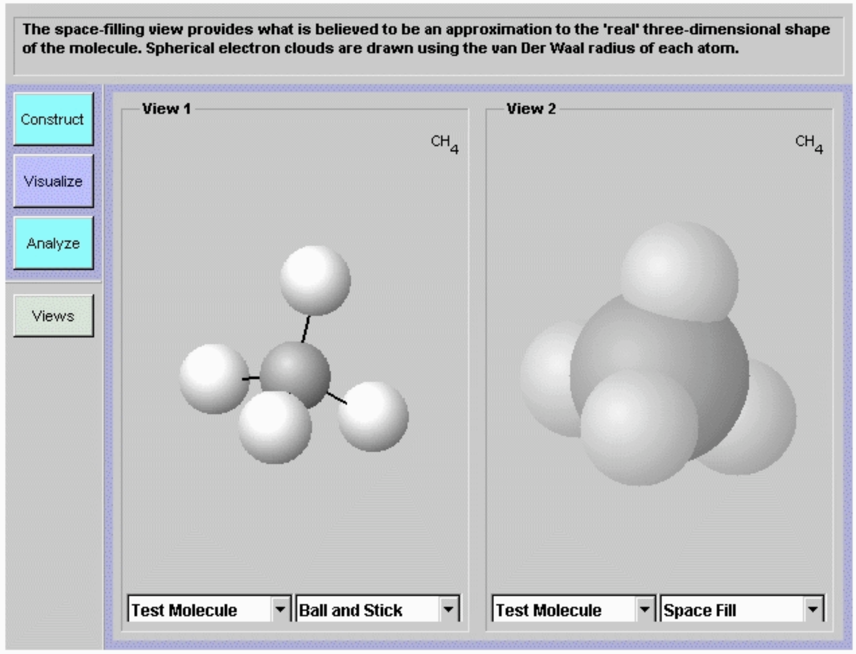

Figure 2. Molecule visualization workspace from eChem

Teachers have their own challenges in terms of sense making in inquiry-oriented science instruction, which software can also help address. We have developed Knowledge Networks On the Web (KNOW), an environment meant to provide scaffolding to teachers grappling with the challenges of enacting complex, inquiry-oriented curriculum materials (Fishman, 2003). KNOW is designed around standards-based, inquiry-oriented, and technology-rich curriculum materials, and uses videos, student work, and other materials and resources designed to help teachers understand how to interpret curriculum so that it becomes more useable in their local contexts. KNOW provides teachers with access to a level of detail and customization that is impossible to achieve using traditional text-based materials, but is ideally suited to the web. Furthermore, KNOW supports ongoing asynchronous conversations about how to teach specific curricula, linked to an organically growing set of examples and elaborations, generated jointly by the community of teachers using KNOW and by curriculum developers. KNOW is designed to leverage the supports provided by curriculum designers with support gleaned from the community of those who have already used the curriculum, and thus have context-relevant experiences to share. Teachers who use KNOW employ it variously as a substitute for and an enhancement of face-to-face professional development, as a planning tool, and as a community forum and collaboration environment. Our intent in designing KNOW was to extend the "educative" nature (Davis & Krajcik, 2005) of printed curriculum materials. KNOW is different from other online teacher learning environments in that it is built around specific curriculum materials, as opposed to more general concepts or instructional strategies (such as inquiry or collaborative learning), and thus serves as a scaffold for teachers learning how to enact that curriculum successfully (Fishman, 2003). KNOW embodies an approach to teacher learning that we refer to as "practice-based professional development," which means that the professional development is centered around helping teachers with practices that they will attempt to enact in their classrooms in the near future.

KNOW can help teachers make sense of complex inquiry teaching practices by also providing teachers with inspectable representations of teaching practice in the science classroom. Specifically, KNOW shows multiple examples of teaching and breaks down an otherwise dense classroom process into understandable chunks. Taking advantage of the ability to show video online, KNOW features "images of practice" videos that demonstrate particular pedagogical techniques such as establishing a relevant context through the use of driving questions (Singer, Marx, Krajcik, & Clay Chambers, 2000). These videos help teachers to form a vision of how certain instructional techniques look in real world classrooms. Because we can provide multiple video examples for any given lesson, it is possible to allow teachers to select an example that matches their own context (for example, leading an activity in a classroom with five computers versus in a computer lab where the student to computer ratio is 1:1; see Figure 3). KNOW also contains more straightforward "how to" videos, which are tutorials on how to set up and carry out particular scientific apparatus or demonstrations. These types of videos also provide scaffolding for scientific sense making, though in a slightly different sense than the "images of practice" videos.

Scaffolding Process Management

Aside from helping make sense of scientific content, learners also need support to engage in and understand scientific practices. The inquiry process can be complex for students and teachers because of its multi-faceted, open-ended nature, which includes a range of activities, many of which will be new to students. Therefore, students and teachers need a range of support to help them manage, navigate, and understand individual process activities and the overall process as a whole. Scaffolding features can support learners in managing their scientific inquiry in several ways.

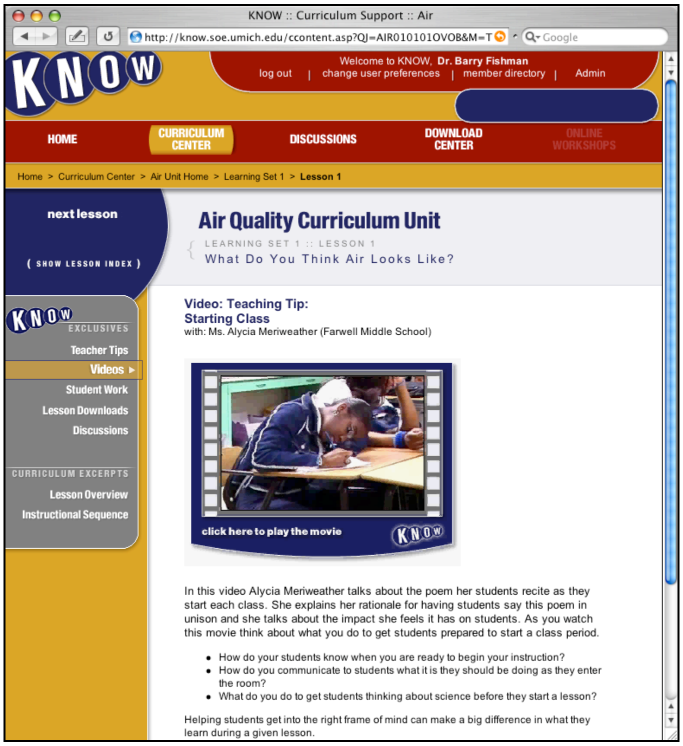

Figure 3. An "images of practice" video page from KNOW.

First of all, scaffolding can provide structure for the complex multi-faceted tasks that learners face in science inquiry. Since students new to science inquiry may not necessarily know their activity options nor the procedures for carrying out certain tasks, one scaffolding approach involves providing ordered and unordered tasks decompositions to learners. Graphical process maps can provide such decompositions through visual descriptions of the activity spaces that comprise different aspects of inquiry activity. One example can be found in Symphony, a scaffolded work environment for science investigations (Quintana et al., 1999). Symphony integrated a range of tools, such as planning tools, databases, graphing tools, etc., behind a scaffolded interface that primarily aimed to support students with the inquiry process. We can illustrate one instance of process management support with the main process wheel (Figure 4), which displays the major tasks involved in a science investigation to show students what their activity options are as they proceed through an investigation.

Another similar example can be found in the Digital IdeaKeeper, which is another scaffolded work environment that supports students with online inquiry practices. In online inquiry, students use digital libraries and other online repositories to find articles and information, and then read and analyze the information they find to answer their science questions (Quintana & Zhang, 2004a, 2004b). The IdeaKeeper also provides activity option information through the tabbed notepad that students use while reading and taking notes on articles and other information resources they have found in digital libraries (Figure 5). The tabs in the notepad describe the steps students should follow as they read, reminding them that effective reading should involve a multi-step process where they first skim an article, read the article more deeply, and them summarize what they learned from their reading.

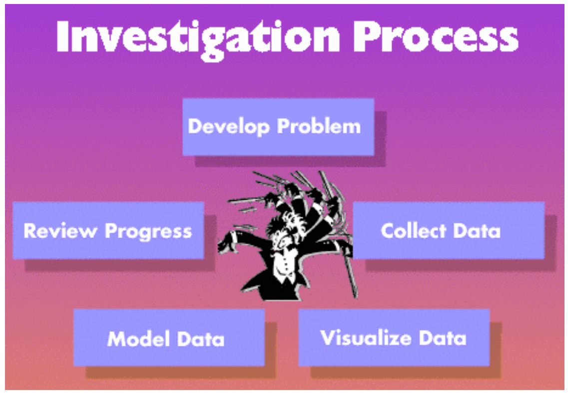

Figure 4. Main inquiry process wheel from Symphony

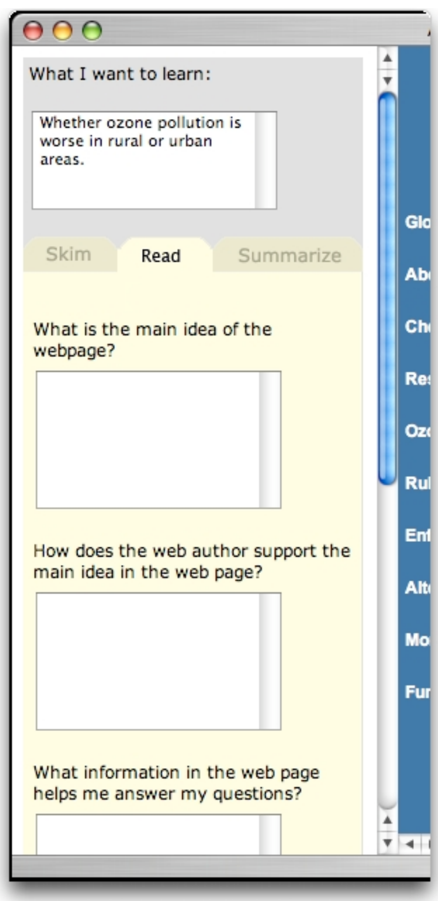

Figure 5. Scaffolded notepad from the Digital IdeaKeeper

Aside from describing the nature of tasks, software can also support students by embedding expert guidance about scientific practices to illustrate the purpose of different activities or the meaning of different science terms. Such support can make the rationale for different inquiry activities explicit to students so they can decide on their next steps at different points in the investigation. For example, the Symphony process wheel introduced earlier also contains activity rationale guides that students can trigger to see a brief description of the different activities shown in the process map (Figure 6). Thus the combination of the process map and rationale guides can help students see both their activity options and the purpose for each inquiry activity.

Figure 6. Activity rationale guides on the Symphony process wheel

The previous scaffolding approaches describe how different aspects of the science inquiry process can be made more apparent to students so that they can effectively manage and proceed through the inquiry process. But another approach for supporting process management involves helping students maintain their focus on their work by automatically handling the non-salient activities that do not necessarily have any intellectual impact on students' science learning. Consider that science inquiry involves managing a range of tools and artifacts, but such management tasks are not necessarily a part of their intellectual inquiry activity and can instead distract students from the more important aspects of their work. Software can provide mechanisms that automatically handle many of these management tasks for students to prevent cognitive shifts between salient inquiry activities and non-salient management tasks. For example, the IdeaKeeper automatically saves various artifacts that students create in easily accessible areas so students do not have to explicitly interact with the computer file system to save and retrieve their inquiry artifacts. When learners save websites that they find interesting, IdeaKeeper automatically saves those websites to the "Reading What I Found" section of the IdeaKeeper sidebar (Figure 7). Additionally, when students take notes on a given website, their notes are automatically saved with the corresponding website. Students do not have to worry about managing or recalling the location of their websites and notes since the sidebar is always visible and accessible to students.

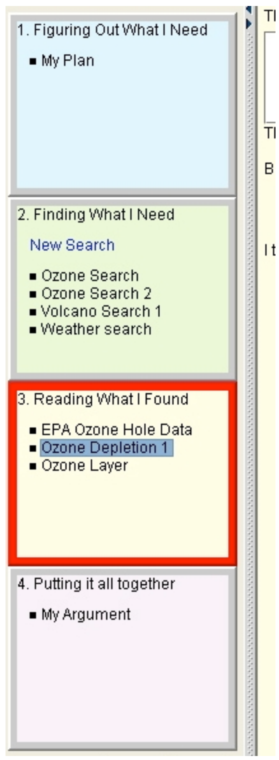

Figure 7. Artifact sidebar from the Digital IdeaKeeper

Teachers also need support in managing the scientific process for students. Again, we present KNOW as a form of software-based scaffolding for teachers learning how to support students engaged in scientific inquiry. For example, "teaching tips" incorporated into KNOW for each lesson embed expert guidance about inquiry practices in science classrooms to help teachers understand how to manage scientific processes with students. Teaching tips are just what they sound like – information culled from both curriculum developers and more importantly from other practitioners that go beyond what is contained in printed curriculum. These text-based tips are not literal process support. Unlike the process maps in Symphony, for example, they are not necessarily meant for teachers to use *during* activity. We have, however, been experimenting with concepts such as "KNOW-to-Go," which are process-oriented scaffolds that teachers can print out or place on handheld computers for reference during class to help them keep track of what they need to do in the context of a particular lesson.

Another kind of process support for teachers involves managing the overall arc of an inquiry-oriented curriculum, as opposed to within-lesson management issues. This can be challenging for teachers who do not have much experience with inquiry-oriented curricula. We have observed that many teachers have trouble with time management, resulting in units that can take far longer to enact than originally designed (Blumenfeld et al., 2000). Frequently, when a teacher feels that they have taken too long enacting a particular unit (for instance if they are feeling pressure to "cover" a certain number of topics in a school year), they will end the unit prior to reaching its specified conclusion (Lin & Fishman, 2004). When a teacher does not have a thorough understanding of the curriculum designer's assumptions with respect to the flow of a unit, their decisions about how to shorten the unit are unprincipled. An extended curriculum has key dependencies built into it. For instance, a modeling activity may be repeated three times, with each repetition adding a different element of the scientific process for students. A teacher who does not understand this, however, will likely not view the three activities as a unit and consider it sufficient to have completed only one. This is symptomatic of what we have referred to as a "checklist" mentality with respect to inquiry-oriented instruction, in which teachers translate inquiry into a series of disconnected activities (Lin & Fishman, in press). To address these issues, we have begun to develop a tool within KNOW called the Planning Enactment and Reflection Tool (PERT; Lin & Fishman, 2004). PERT describes the composition of extended curriculum by making the implicit between-lesson connections and the goals of individual lessons more explicit for teachers. This way, when teachers make choices about how to shorten or otherwise adapt curriculum materials, their choices do not create conflicts or problems for the larger inquiry-oriented goals of the curriculum. PERT does this by allowing teachers to indicate in advance what parts of a unit they are likely to teach and which they are likely to omit. PERT then uses a dashboard metaphor to show teachers the match between the opportunities for meeting particular scientific process goals if the unit is taught as designed and the match that will exist if the teacher enacts the unit as currently planned. Where there are large mismatches (and possibly problematic or "lethal" mutations in unit enactment; (Brown & Campione, 1996), PERT helps point teachers to areas in the curriculum they might focus on to address the gaps (see Figure 8 below).

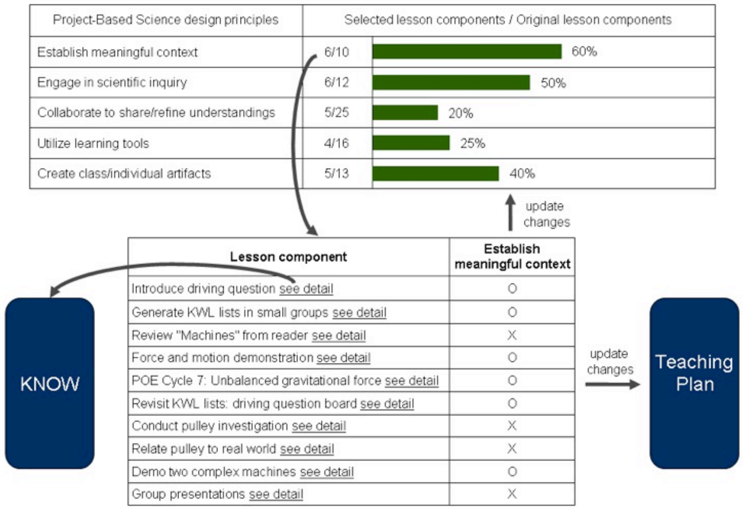

Figure 8. Mock-up of process evaluation dashboard from a prototype of PERT.

Scaffolding Reflection and Articulation

The previous two scaffolding categories addressed the different content and process aspects of science inquiry. However, another important aspect of learning that impacts both of these involves reflection and articulation. Different perspectives on learning describe the importance of reflective activity to develop understanding (Bransford, Brown, & Cocking, 2000). While reflection and articulation are important for learning, students may also need extensive support to make them aware of the importance of effective reflection and articulation and to help them see what they should reflect on and articulate at different points of their inquiry.

Scaffolding features in software can support learners with reflection and articulation throughout their science inquiry. A common scaffolding approach involves the use of prompts and text areas in the software interface. For example, textual prompts can convey to learners important things they should think about with respect to the science products they generate and information they analyze throughout their work. Software can also support articulation by using text areas, usually coupled with textual prompts, to give learners an explicit area to record different types of information. For example, the scaffolded notepad that we described earlier from IdeaKeeper also incorporates prompts and text areas to help students analyze and make sense of the different articles they may find in a digital library (Figure 5; Quintana & Zhang, 2004b). When students view a website or article, the notepad is displayed in a window alongside an empty notepad. The prompts in the notepad describe to students the different things they should think about as they skim, read, and summarize the article (e.g., the main idea of the article, the support provided by the article's author, the utility of the article for the student inquiry, the bias that may or may not be displayed in the articles, etc). Additionally, the text areas in the notepad give students a space to record notes pertaining to the different prompts for further review.

Software can support other aspects of reflection and articulation that may not be so apparent. Aside from reflection and articulation in the context of scientific products and information, students also need support for reflecting on and articulating aspects of their work, such as the plans for and progress through the inquiry process. Effective planning and monitoring pose particular challenges for learners, and given the open-ended, multi-faceted nature of the science inquiry process, students need explicit support for helping them constantly take stock of their previous work and make decisions about the subsequent directions of their inquiry. For example, the Symphony process wheel (Figure 4) is paired with a plan/log grid (Figure 9) that serves as an explicit area where students can articulate their plans and keep track of their progress as they iterate through the inquiry process. Students set up investigation plans by dragging activities from the process wheel and dropping them in the plan row of the plan/log grid. Students can also modify their plans by moving activities to different slots in the plan. As students complete a given activity, the icon for that activity drops from the plan row to the log row, indicating that they have worked on that aspect of the plan. Since the process wheel and plan/log grid are constantly visible, students can incrementally add to their plan throughout their work.

Figure 9. Symphony Plan/Log Grid

The PERT component of KNOW presented in the previous section also supports teachers' reflection on their own teaching in inquiry-oriented instructional environments. PERT, which was initially conceived as a planning tool, does this by inviting teachers to return to the system after teaching and update their records by articulating what parts of the curriculum they taught, omitted, or adapted in ways beyond what is specified in the curriculum materials. The process of making past teaching activity explicit in this way fosters teacher reflection, which is a key component of intentional improvement. In this way, reflection and planning (for future enactments) are intimately connected. Our own related research on teacher learning has revealed the importance of revisiting prior teaching iteratively in professional development (Kubitskey & Fishman, 2005), in effect switching between planning and reflection, in order to help correct misconceptions and flag problem areas for future focus.

Aside from PERT, KNOW contains additional tools to support teacher reflection and articulation, such as discussion boards where teachers are encouraged to both ask questions and share reflections on particular enactments. These reflections are occasionally culled and reified as "teaching tips" in the curriculum sections of KNOW (Fishman, 2003). These approaches and others are all valuable as vehicles to promote articulation and reflection among teachers.

Concluding Remarks

Research on scaffolding continues to uncover a variety of approaches that different agents can employ to support learners as they engage in complex intellectual practices. Traditional views of scaffolding that focus on human interventions to support learners now encompass an additional focus on software interventions that scaffold learners in similar ways. In this paper, we have focused on scaffolding features for software that scaffold learners with science inquiry practices in classroom settings. While scaffolded software has focused mostly on supporting students, we have also discussed how software can support teachers with their teaching practices in science classrooms. When we consider scaffolding under these perspectives of "student as learner" and "teacher as learner", we can see how software can actually play a dual role to connect the human and software aspects of scaffolding. Certainly, when the main audience for scaffolded software includes students, the software is providing a direct scaffolding function for those students. However, when the main audience for scaffolded students includes teachers, the software is also indirectly supporting students by directly helping teachers strengthen their teaching practices to essentially become a more effective human scaffolding agent. While we have specifically focused on scaffolding in a science inquiry setting, this dual support focus is not restricted to a science setting. An interesting research direction would be to consider scaffolding in other contexts and content areas for both students and teachers to uncover similarities and differences in both the conceptual scaffolding approaches and the manner in which those approaches can be implemented in software. By extending previous scaffolding work to also focus on teachers, we can essentially help to develop a wider range of scaffolding strategies that can be provided by both humans and software to the ultimate benefit of students in classroom settings.

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