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Developing Reflective Inquiry Practices: A Case Study of Software, the Teacher, and Students

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A group of students has decided to investigate Pluto's erratic orbit around the Sun. Their goal is to set up computer simulations with different configurations of planets orbiting the sun to determine which planet has an effect on Pluto's orbit (e.g., a simulation with only Pluto and the Sun; a second simulation with Pluto, Neptune, and the Sun, etc.). They gather some information about Pluto, the Sun, and other planets, such as mass, distance from the sun, length of an orbit, etc., and plan on using these values to set up the simulation. They have been working with the teacher to develop this basic research methodology, and everyone, including the teacher, is satisfied with the viability of this approach.

But when the students begin to set up the simulation using the simulation environment Interactive Physics, they begin to encounter problems. There is a significant mismatch between the information they gathered and the variables they can change in the simulation. The students are overwhelmed by the number of variables and do not know which to try and which are irrelevant. Should they change the gravitational constant, orbital velocity, *xy* coordinates, initial velocities, mass, or diameter? Moreover, the units of measure of the information they gathered are different from the units of measure used by the simulation (e.g. the data they collected was in kilometers per year, whereas the simulation required meters per second), adding another level of complexity.

As the students try different values, it soon becomes clear that it is a challenge to simply get any object to orbit another object, let alone set up a simulation that reflects the dynamics of our solar system. As they try to figure this out, the students set a variable and then run the simulation to see if it worked. But because some of the values were wrong, or some variables were overlooked, planets would fly into the Sun, or shoot off into space. So the students change a second variable, and run the simulation again. When that also does not work, they tweak the simulation, and try another value. Since nothing works, the students feel that they never find any of the "right" answers or relevant results, so they do not write anything down.

At the end of the class, when the teacher comes around to check their progress, she finds a struggling group of students who are somewhat able to articulate what they are doing but have no record of their work over the course of the period. The students have clearly been working throughout the period, but is their struggling a sign of progress or haphazard thrashing? How can the students learn from what they have explored so far to decide on the next steps of the investigation?

This example illustrates the kinds of challenges that arise when students do inquiry in science classrooms. Opening up laboratory work to student-generated questions and methodology means that students are not always going to "succeed" in their projects. The challenges presented by this example represent a progression of opportunities for learning and some partial success, rather than a project that failed completely. Students need to learn inquiry skills that help them to systematically pursue a solution to their question and to better manage their process of inquiry. To be successful in inquiry, they need to develop new habits and new conceptual frameworks that redefine the pursuit of science as a process of constructing new knowledge rather than a search for simple answers.

Seeking to understand the skills, the requisite dispositions, and the mechanisms for helping students develop into *reflective inquirers* is the goal of the Supportive Inquiry Based Learning Environment project (SIBLE). We are conducting iterative design research on the challenges faced by students as they work in information-rich environments and how their development of investigation skills can be facilitated through interactions with a software support tool and the classroom teacher. We developed a software support tool, called the *Progress Portfolio*, as an integral part of this research process. Our research is concerned with how to craft not just the software to foster reflective inquiry, but the whole learning environment, including the interactions among students, teachers, and materials.

In this chapter, we describe our initial foray into this process of supporting reflective inquiry in the context of a high school physics class. We describe the first iteration of our software design, and through a case study, explore how these tools can be integrated into the practices of an existing curriculum project. Our goal is to understand what it looks like when students are conducting these complex data-rich investigations, what kinds of supports are needed to foster reflective inquiry, and the shifts in thinking that students need to make as they learn this different mode of work.

The Need for Reflective Inquiry

Current science standards mandate that students learn the process of inquiry in scientific domains (AAAS, 1993; NRC, 1996). The goal is for student learning of scientific content to be grounded in an understanding of the processes of scientific investigation and their application to real problems. Despite this goal, much of science is still taught as a process of memorizing facts and conducting scripted confirmatory laboratory exercises (O'Sullivan, Reese, & Mazzeo, 1997). An inquiry approach to learning science needs to center around scientific process, not scientific facts (NRC, 1996; O'Sullivan et al., 1997). Students should be engaged in active inquiry, asking questions, gathering data, analyzing data, drawing conclusions, and communicating results (Linn, Songer, & Eylon, 1996).

These goals require a major shift in science curricula and teaching. Doing inquiry, especially open-ended inquiry, remains a challenge for both students and teachers. Students are rarely given the opportunity to pursue and manage their own research questions. Instead, they are often given tasks to do without a corresponding understanding of the purpose and goal of the task. They are given step-by-step instructions on how to reach that goal, relieving them of the need to thoughtfully engage with the content. This approach leads to students working without a clear understanding of how their investigation is situated within the practices and understanding of science. They develop skills, habits, and expectations about the nature of schoolwork that can hinder their success in conducting inquiry (Schauble, 1990). Students often develop an objectivist orientation towards science, viewing the process of science as seeking facts rather than the construction of knowledge (Tobin, Tippins, & Hook, 1995). They become accustomed to a non-reflective, action-oriented mode of work (Schauble, Glaser, Duschl, Schulze, & John, 1995).

Recent developments in educational technology hold promise in providing rich environments in which students can pursue and manage their own investigations. These classes of investigation tools include data visualization software (e.g., WorldWatcher, Northwestern University; Earth-View Explorer, Columbia University), simulation environments (e.g., GenScope, BBN; Interactive Physics, Knowledge Revolution), modeling tools (e.g., ModelIt, University of Michigan), web-based information sources, and digital libraries of text, images, and video. These software tools enable students to query or generate their own data sets, to construct visualizations representing complex phenomena, and to set up and run their own simulations.

These software tools, in turn, open up new avenues for science activities in the classroom. While there are a myriad of ways to make science learning more constructivist in nature, these investigation tools afford a style of project-based work that takes advantage of the richness and complexity of data to provide authentic science opportunities (Soloway, Krajcik, Blumenfeld, & Marx, 1996). They afford student projects that make use of large amounts of data, providing students with a wide range of opportunities to pursue their own questions and construct their own explanations. They also afford extended projects in which students have the opportunity to learn how to manage and coordinate data collection and interpretation activities.

In addition to creating opportunities for inquiry, the introduction of information-rich computer environments can create new challenges for students. Students can become overwhelmed by the wealth of information and have trouble managing and making sense of it. They become mired in the activities of the investigation process, generating data, tweaking simulation variables, and exploring new hyperlinks, losing sight of their questions and purpose. The process through which students generated, analyzed, interpreted, and drew conclusions from data can be easily lost as students often can not remember what they did and fail to document their procedures. This problem is compounded with work in a digital medium, where the interim steps in the investigative process can be transient. While work with pencil and paper can leave a trail of artifacts, work in a digital medium often consists of little more than a series of mouse clicks. This lack of a concrete representation of the inquiry process can make it a challenge for students and teachers to review and discuss the process of the students' investigations. If students are to learn scientific process, they must have the means to reflect on and learn from their own investigative process.

Reflection, the act of stepping back from one's activity to view actions, objects, system states, or emerging understandings from a different perspective, is widely cited as an essential component of learning. *Learning* is itself a reflective process wherein students integrate new knowledge through a process of accommodation, in other words, reflecting on and transforming prior conceptions to account for new information (Perkins, 1998; Pintrich, Marx, & Boyle, 1993). In order to improve upon their own investigation and learning processes, students need to think metacognitively, to reflect on their work (Glynn & Duit, 1995). They need to be self-monitoring, to engage in strategic planning, reflect on strategies used, and evaluate the outcomes of using these strategies (Collins & Brown, 1988; Davis, 1996; Schauble, Glaser, Raghavan, & Reiner, 1991; Schoenfeld, 1987). Students also need to maintain goal orientation in inquiry, being mindful of the goals and subgoals that constitute scientific discovery and reflecting on these goals in the context of an investigation (Schauble, Raghavan, & Glaser, 1993; Shute & Glaser, 1990).

As is the case with investigation environments, technology can offer some compelling solutions for supporting reflection. Existing software support for developing these reflective skills falls mainly into two categories: self-contained, content-embedded investigation environments with built-in reflective supports (Schauble et al., 1993; Shute & Glaser, 1990; Tabak & Reiser, 1997; Tabak, Smith, Sandoval, & Reiser, 1996); and domain-general communicative structures designed to promote reflection (Edelson & O'Neill, 1994; Scardamalia, Bereiter, McLean, Swallow, & Woodruff, 1989; Suthers, Weiner, Connelly, & Paolucci, 1995). Content-embedded investigation environments have the advantage of being able to directly scaffold student thinking in domain-specific ways. For example, in the Biology Guided Inquiry-Based Learning environment, the software is designed to provide content-specific prompts that scaffold students as they construct explanations of evolutionary processes (Tabak et al., 1996). The disadvantage of this approach is that the scaffolding is limited to one particular project or one particular domain. In contrast, domain-general software supports provide more flexibility by being able to support different projects in different domains. For this latter class of tools, scaffolding is usually targeted at a generic inquiry level. For example, the Collaboratory Notebook (Edelson & O'Neill, 1994) scaffolds student discussions by helping them articulate the logical structure of a discussion, labeling their contributions to the discussion as "conjectures," "questions," and other rhetorical devices.

Both classes of software support provide students with some form of trace or record of their inquiry actions, allowing students to observe their own problem solving behavior after they have reached a solution, and perhaps comparing it with other solutions. For example Schauble, Raghaven, and Glaser's (1993) Discovery and Reflection Notation system provides software artifacts that show students a visual representation of the steps they took in their investigation, which can be used by students to reflect on their work and plan their next steps. Similarly, Collins and Brown (1988) describe the utility of computer artifacts in reifying the learner's actions so that they can become objects for reflection.

Our work builds upon this research to develop an understanding of reflective inquiry and inform the design of software and curriculum to promote this style of work. We are interested in a particular curricular context: investigations in which students work with large amounts of data, develop their own research questions, and need to manage a long-term project. We want to understand how to help students to create a trace or record of their investigations in the context of data-rich environments, and how to build domain-general supports that are useful across different kinds of data-rich investigations. At the same time, we want to understand how prompting—both content-specific and generalized prompting—might be tailored to help students focus on important issues in their investigations. We also want to understand how to facilitate the process of learning these reflective skills: Not just supporting student work, but understanding how to create opportunities for learning conversations between students and teachers. In addition, we want to understand how to support the activity of teachers in these contexts. Specifically, we want to understand how to provide teachers with a way to periodically assess student progress on long-term projects, to establish milestones, and to see what students are doing and thinking. In short, we are seeking ways of promoting reflective inquiry through the coordinated efforts of teachers, software, and curricular activities.

Three Components of Reflective Inquiry

Reflective inquiry is a style of inquiry that encompasses both effective inquiry strategies (e.g., systematically collecting and interpreting data) and reflective activities (e.g., monitoring, periodically evaluating progress, and revising plans). It focuses student attention on both the results of investigations and the inquiry process itself. Students need to be reflective inquirers in order to successfully complete their projects, gain a deeper understanding of the domain content, gain a better understanding of the scientific process, and improve their science skills.

Reflective inquiry can be characterized as three primary sets of activities. We will briefly outline the components, and develop the ideas more fully as we work through the examples in the rest of the chapter. The three basic activities are:

1. *Creating a record of progress:* A reflective inquirer needs to carefully record the activities of an investigation, ranging from gathering background information, to how an experiment is set up, to the results of particular experiments, and interpretation of the results. This record also needs to be carefully organized and managed.
2. *Monitoring progress*: In addition to creating a record of activities, a reflective inquirer also needs to monitor the progress being made in an investigation, reviewing and reflecting on where one has been, and revising investigation strategies to improve progress toward the goal.
3. *Communicating process and results to others:* Finally, an equally important aspect of reflective inquiry is being able to communicate one's process and results to others. While monitoring is a more obvious reflective activity, the act of communicating (as well as creating a record) can serve as a catalyst for reflective activities. To describe one's process and results, one must first step back from the activity itself and reflect on the salient or important aspects of the investigation.

Software Tools for Reflective Inquiry: The Progress Portfolio

We designed the Progress Portfolio to be a catalyst for these three reflective inquiry activities. Our basic approach to supporting reflective inquiry with the Progress Portfolio can be summarized by two design principles:

Tools for Creating Concrete Artifacts

First, our basic approach to promoting reflective inquiry revolves around the notion of creating concrete artifacts to anchor reflective processes. In order to reflect, one must have something to reflect on. We designed the tools of the Progress Portfolio to enable students to create artifacts that represent the evolving states of their investigation process. Our goal is for students to construct a record of their progress that can help them monitor their progress and communicate. These artifacts then serve as the objects of reflective conversations as students discuss their investigative process with fellow students and teachers. The artifacts also serve as objects of reflective actions, as students manipulate, organize, and construct narrative representations out of these artifacts using the tools.

Providing a Task Model

Second, we designed the tools of the Progress Portfolio to serve as an implicit task model for reflective inquiry. The tasks of creating a record, monitoring, and communicating are directly supported by our tools. Rather than asking students to create their own methods and representational forms for reflective inquiry, the Progress Portfolio provides tools and an implicit model for being reflective inquirers. The task model is "implicit" in that it suggests tasks, but relies on the students' initiative for action. Students use the Progress Portfolio as they conduct their investigations in other investigation environments. They use the investigation environment's tools for exploring content (e.g., Newtonian physics, urban planning), and simultaneously use the Progress Portfolio tools to create a record, monitor, and communicate about their work in the investigation environment. In this way, students are creating tangible representations of their ongoing work processes using a tool that guides them towards establishing the skills for these important scientific practices.

The Progress Portfolio Tools

As students conduct their investigations in other investigation environments (e.g., Interactive Physics), they use the Data Camera tool (see Figure 1) to create a record of their work. The Data Camera works by capturing a picture of their investigation environment screen. These screenshots are then saved onto pages in the Progress Portfolio. All data collected into the Progress Portfolio resides on individual pages, which can contain picture fields for the screenshots, text fields, and sticky notes (more on these later). As students work through their investigation, they create numerous pages that represent various states and intermediate products of their investigation. For example, a student might create a page that represents their investigation screen when they are first setting up an experiment, and a second page to document the results of the experiment. These pages then serve as concrete instantiations of important stages of the student's work process, providing a reminder of what the student did.

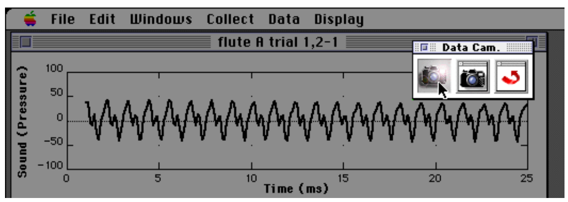

Figure 1. Data Camera tool. Clicking on the camera captures the screen of the investigation environment. Here the data camera is being used to capture a graph of a sound wave generated by a flute using Sound 3.01 software.

Capturing the screen using the Data Camera makes it easier for students to document many aspects their work. For investigation environments like Interactive Physics, documenting a simulation trial can be a tedious and visually intensive task. For instance, to properly document each trial, the students would have to record how many planets were present, the mass and distance/location of the planets, any changed parameters (e.g., gravitational constant, radians), and the results. Results of these simulation runs pose an especially difficult challenge as they are graphs of velocities and visual depictions of the orbital track of the planets. To record this kind of information using pencil and paper, students would have to sketch the resulting graphs and orbital tracks on a piece of paper.[1] The Progress Portfolio simplifies this process by making it easy to capture the screen and annotate variable values directly on the captured data.

1. Though some of this documentation could be done with a printer, not all classrooms have ready access to printing, nor the resources to allow each student to print out and keep track of multiple pages. The software allows comments to be integrated within the captured screen, and more effective access and organization than is possible with paper copies only.

In addition to holding screenshots, students can also annotate their pages with sticky notes and text fields. Sticky notes are like their physical counterparts (Post It™ notes), in that students can write short notes and then "stick" them onto a page. In addition, sticky notes have arrows that students can use to point out notable features on the screen, such as the peak of a graph. Students can use sticky notes to both record how they set up an experiment, and to help them remember how they interpreted the results of an experiment. Rather than simply taking a snapshot of their investigation work, sticky notes provide students with a way to attach metacomments about the images that they capture to help them remember what they were doing, or what they found interesting about the particular image they captured (see Figure 2).

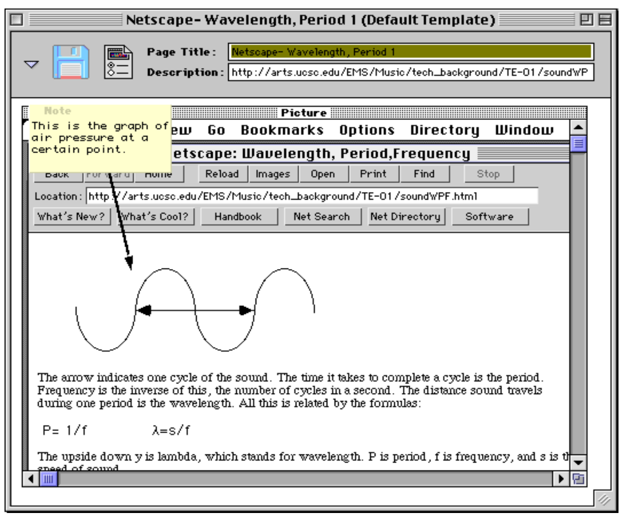

Figure 2. Students capture graphics and text from a web site onto a Progress Portfolio page and annotate it with a sticky note to help them remember why they captured it.

Text fields are similar to sticky notes in that they are intended to help students record their thoughts as they work. But they also have an advantage over sticky notes in that the teacher (or curriculum designer) can customize a text field with prompts to help students monitor and reflect on their progress. For example, text fields might be tailored to support generalized investigation strategies with prompts for "observations," "notes," and "next steps." Or, they might be more specifically tailored to a physics simulation, prompting students to record "What variables in the simulation did you change?," "What was the result?," and "Was this what you expected?" Prompted text fields help students develop reflective inquiry skills by reminding them to create a record of their progress (similar to the way a science notebook might be used), and prompting students to reflect. In addition to these process-oriented prompts, content-specific prompts could be created. For example, for a planetary motion investigation, the prompts could be tailored to help organize the conceptual space by focusing students on key variables that they need to change (e.g., masses, distances, and forces at work). Because these metacognitive prompts are customizable, teachers or curriculum designers can tailor them to help students reflect on specific aspects of their work (Davis, 1996). Moreover, using a common static page type across different activities or various phases of a student project (e.g., literature search, data collection, and presentation) can help reinforce skills, as students are repeatedly prompted to record observations, next steps, etc.

Pages themselves can be customized to promote monitoring and reflective activities by encouraging students to analyze and review the data they have collected in new ways. For example, one kind of customized page is a comparison page where students can place two or more captured images side by side in order to compare and contrast data (see Figure 3). Students can compare three graphs of sound waves created by different musical instruments and begin articulating hypotheses about what causes the instruments to sound different, and set new plans for collecting and analyzing data to confirm these hypotheses.

The Progress Portfolio also provides tools to help students organize and make sense of their documentation pages. Students can cluster thematically related pages together into folders to help them keep track of their pages and their investigation. For example, in exploring a simulation of planetary motion, students might put all of their experimental trials varying the distance between the Sun and the Earth together into one cluster, and their experiments with varying mass in another cluster. These clusters can help students monitor and reflect on how their data collection is progressing. As students collect more and more pages, keeping the pages together in a flat list can make it difficult to see what they have. Encouraging students to review their pages and develop an organizational structure can help them keep track of the data they have and see where data might be missing from their investigation.

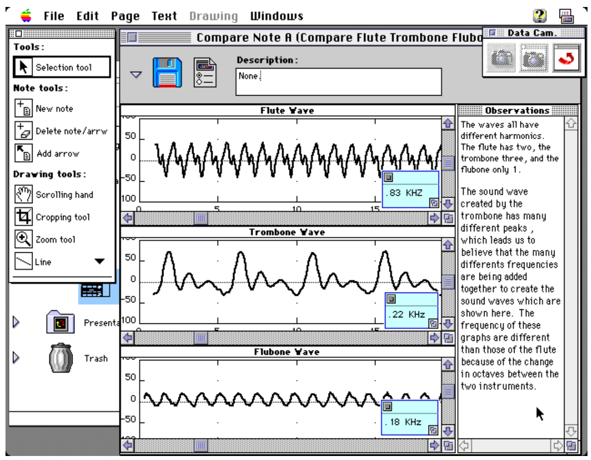

Figure 3. A Comparison Page. Students have constructed a comparison page in the Progress Portfolio using graphs to explore the similarities and differences of sound waves generated by three different musical instruments.

Communication is implicitly supported by many of these tools. Rather than mediating student communication, as other software, such as the Collaboratory Notebook does, the artifacts created in the Progress Portfolio afford reflective, face-to-face conversations. As students construct Progress Portfolio pages, they can discuss with each other what to document and how to document; what aspects of their investigation warrant documentation, keeping track of their plans and changes in the direction of their project. They can review their captured images as they plan their next steps. Teachers can engage students in conversations about what they are doing while looking through the students' work in the Progress Portfolio. In particular, the captured pages in the Progress Portfolio provide the teacher with a window into student conceptions of the task (e.g., what students capture and do not capture reflects their understanding of the value of different aspects of the inquiry process), student understanding of the science concepts (e.g., their written annotations can reveal their level of understanding), and the students' ability to interpret and analyze data (e.g. the teacher can review the original captured screens from the investigation to verify the students' interpretations of the events, rather than relying only on the students' interpretations of the data).

The Progress Portfolio also has presentation tools that more explicitly support communication. The presentation tools facilitate communication by giving students the ability to easily review their work and create a slide presentation to enhance an oral or written report. In the process of creating the presentation, students need to reflect on their investigative process; they review their captured pages to select the pages that best represent their investigation or help them to explain their process and their results. They create presentations by copying these pages into a presentation area, then reorder, revise, clean up, and add annotations to create presentation "slides." These presentation tools make it easy for students to go back and look at what they did. Their earlier efforts in creating documentation artifacts during their investigation take on new value as they re-purpose these artifacts for their presentation. Not only do their collected pages help them recreate their investigations, but they are also useful for illustrating their work. Teachers can also guide students to focus on specific aspects of their investigative process, encouraging students to reflect on the rationale for plans taken, the fate of different solution strategies, or how the students' ideas have evolved during the investigation. In creating and presenting the story of an investigation, reflection becomes a part of the work of doing the investigation, rather than an added-on activity serving no obvious purpose.

Taken as a whole, the tools of the Progress Portfolio promote reflective inquiry as students create and document artifacts that represent their investigative process, have reflective conversations around these artifacts, and are prompted to make sense of and present a story of their investigation. The Progress Portfolio provides a common repository for student work, a place where they can gather together all of their information for synthesis, analysis, and reflection. Student use of the Progress Portfolio can create learning opportunities as teachers review the trace of students' investigations and talk with students about their progress, point out mistakes, and suggest strategies for documenting. Students learn to engage in these reflective practices in action as they progress through their investigation, rather than just at the end of the investigation. Used together with an investigation tool, the Progress Portfolio promotes reflective inquiry by providing a concrete space for students to create a record, monitor, and communicate about their work.

The Focus of This Chapter: An Analysis of Steps Toward Reflective Practice

Designing software to promote reflective inquiry only addresses a small part of the challenge of promoting reflective inquiry. How software is used or not used in a classroom is determined by how teachers take advantage of the affordances of the software, and where students are in their understanding and skills. Successfully promoting reflective inquiry involves the careful coordination of teachers, students, and materials (including, in this case, software) (Ball & Cohen, 1996). Our goal with this chapter is a first pass at understanding the whole context of fostering reflective inquiry: supporting the three components of reflective inquiry (creating a record, monitoring, and communicating) not only with software, but also with teacher practices and classroom activities. This can be broken down into three basic questions:

1. *What kinds of challenges do students face?* What is difficult about working with complex investigations? What role does reflective inquiry play in their work? What shifts in their thinking are needed to move toward these practices?
2. *In what ways is the software effective in supporting reflective inquiry?* Does the task model embodied in the software match the needs of the classroom? How well do the tools support the activity tasks? What do students do with the software? How does the work that students do around the creation, documentation and use of investigative artifacts contribute to their success at being reflective inquirers?
3. *How do teachers make use of the software to promote reflective inquiry?* What kinds of guidance do teachers provide to students? How do teachers make use of the artifacts that students create in the software?

To explore these questions we conducted a pilot study with our first software prototype in a high school physics classroom. In this chapter, we highlight the role of reflective inquiry in the context of a long-term project that students in this classroom conducted. In particular, we describe the students' attempts at a reflective inquiry style of work: the ways in which students engaged in reflective inquiry, how the teacher worked to promote it, and the role the software played. In the rest of this chapter, we will first briefly describe the setting of this pilot study, then explore reflective inquiry through case studies, and finally conclude with some reflections on our design of software supports for reflective inquiry.

The Setting

This pilot study took place in two physics classes taught by Laura, a teacher in a suburban high school near a large midwestern metropolitan area. The classes were of mixed age groups, combining both high school juniors and seniors (ranging in age from 16 to 18 years old). The student population was mostly moderate income, middle-class students. One of the main activities in physics classes at Laura's school was a year-end long-term (6-week) physics project in which students conceived, set up, and ran their own experiments. These projects involved complex computer-based activities where students needed to coordinate and manage large amounts of data and background materials; in short, exactly the kind of project we designed the Progress Portfolio to support. In our initial conversations, Laura felt that bringing in the Progress Portfolio could enhance this technology-oriented project and that students would benefit from its documenting and reflection tools.

The End of the Year Physics Project

Laura and the other teachers in her department had designed the physics projects to address two primary goals. First, they wanted the students to have an opportunity to engage in doing "real" science, where students went through the whole cycle of inquiry, from doing background reading, to generating experimental questions, running the experiment, analyzing the results, and presenting and explaining their interpretations. The second goal was to give the students an opportunity to use computer technology in their investigations. The teachers provided the students with a range of software options, including physics simulation software, laser disc media, spreadsheets, and presentation software. All students were required to use the computer both as a data exploration and analysis tool, and as a tool to construct and present their findings. In the original curriculum, students were asked to create presentations using Apple's HyperCard, a word processor, or web pages.

The teachers guided the students through the task of conducting inquiry using two established formal structures. The whole project was decomposed into subtasks that were laid out for the students in sequence: literature search, topic identification, technology acquaintance, proposal of experiment, data collection, analysis and discussion of results, and presentation. The other formal structuring feature was setting expectations to help students get a sense for how they were going to be evaluated. First, the rubrics for grading were made public, identifying the dimensions that they were to be graded on, and guidelines for scoring each dimension. In addition, Laura demonstrated the grading process by going through a sample project and explaining how she used the rubrics to grade. Students also had opportunities to assess each other's work (peer assessments of rough drafts), in essence giving students practice at critiquing themselves. Finally, Laura assessed student progress at the end of each day, indicating satisfactory progress along six dimensions (measurements, use of class time, journal, project sustainment, teamwork, communication). Students received a rubber stamp on each item that they completed satisfactorily.

Although Laura provided a lot of guidance through the task model, rubrics, and day-to-day interactions, it was equally important to her that the students had an opportunity to struggle in their work, to define their own problems, and find their own solutions. This approach meant that there were times when her students floundered, but this too was seen as an opportunity for learning.

The Two Cases

Laura identified a number of student groups whom she thought would benefit from using the Progress Portfolio. The researchers then gave these students a short demonstration of the Progress Portfolio's capabilities. Two student groups from two separate classes volunteered to use it. One group was described by Laura as consisting of high achieving students (two seniors, two juniors; three males, one female), and the second group were average, or "B" students (two seniors, one junior; all male). These two student groups used the Progress Portfolio with their investigations while the rest of the class did similar projects without using the Progress Portfolio. While this was the most open-ended and longest-duration project in the school's physics curriculum, the students all had experience with similar, though smaller scale projects in other classes, and were relatively familiar with using computers in the classroom.

The students' first assignment was to pick a general domain of inquiry in physics from a set of materials and resources that the teacher provided (e.g., the physics of planetary motion, music and sound, sports, or automobile collisions). Our two groups selected music (high achievers) and planetary motion (average) students. After selecting their topic, they were required to conduct a literature search on their topic (using the school's library and the World Wide Web) to get some background knowledge and begin to narrow down the topic into an investigatable question. All groups were required to use technology to set up an experiment that investigated their questions. Music groups were provided with sound graphing software (Sound 3.01 from Tufts University), and planetary motion groups were provided with Newtonian physics simulation software (Interactive Physics by Knowledge Revolution).

We videotaped the student sessions with the Progress Portfolio and the final presentations for all groups. We also conducted exit interviews, and collected copies of the work they did in the Progress Portfolio throughout their investigations. At least one researcher was always present with the group, primarily providing support on how to use the software. The work in this chapter is based on analysis of videotapes, field notes, and computer artifacts.

Reflective Inquiry in Action

What are the challenges in incorporating a reflective style of inquiry into open-ended science projects? How does the teacher and the software help support reflective inquiry? In this section, we will highlight episodes from the investigations of the two student groups that illustrate the challenges of reflective inquiry and provide evidence of emerging inquiry habits and dispositions. We will discuss episodes in which the teacher or the software fostered reflective inquiry (with varying degrees of success). More importantly, we will see the students' progression of developing an understanding of the reflective inquiry skills and habits involved in creating a record of progress, monitoring, and communicating. We do not expect to see students master all aspects of reflective inquiry immediately. Rather, we will explore how students begin to shift towards reflective inquiry practices, and the challenges they face in this process.

Creating a Record of Progress

In order to be a reflective inquirer, students need to create a record of their thinking, ideas, and decisions, so that they can go back and reflect on, monitor, and communicate their progress. How are students able or not able to create a record of their work with the Progress Portfolio? When do they capture their work? What do these records look like? How can the software and the teacher push students toward better reflective inquiry documentation practices?

Successfully Setting up a Documentation Structure and Routine

Early in their project, one of the student groups demonstrated facility for creating a record by establishing a routine for their data collection activities. For their investigation, the music group had decided on the general task of comparing sound waves from three different instruments: a trombone, a flute, and an instrument they had created called the "flubone." They did not explicitly articulate their research question, but they did establish a general plan of comparing the sound waves generated by these three instruments. They systematically embarked on this task by creating a data table (which was one of the requirements specified by the project rubrics), using it to structure their work as they generated and collected sound waves from the various instruments. The data table was set up to record seven notes per instrument, with two samples of each note and information about how the note was generated (e.g., the fingering used on the instrument to create the note), and the measurements they made (e.g., the frequency, wavelength, and amplitude of each note). After some initial struggling with the sound software (e.g., how to record things, how to analyze, how to play a particular note, why graphs looked different), they quickly settled into a data collection routine.

The data collection routine itself was relatively complex, consisting of multiple steps, some of which were given to students, and some that they developed themselves as they worked (this will be discussed further in the Monitoring section). Collecting one piece of data entailed the following steps: (a) referring to the data table to determine which note needed to be captured; (b) playing the target note on an electronic keyboard to hear what the target note was; (c) figuring out the corresponding note on the instrument; (d) figuring out what sound level lent itself to a consistent graph in the Sound graphing software; (e) recording the note to create the graph; (f) using the Sound software to analyze the graph (to measure the frequency, wavelength, and amplitude); (g) capturing the graph in the Progress Portfolio; and finally (h) recording their measurements on sticky notes and the "observations" field. Figure 4 shows an example of their collected data in the Progress Portfolio. Over the course of approximately 4 class days, the students collected data on 21 separate pages.

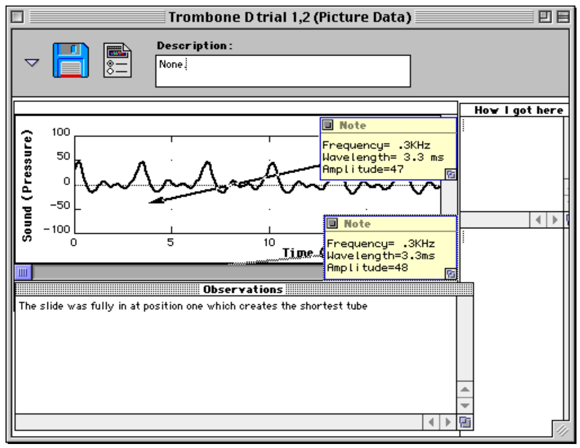

Figure 4. Students in the music group used the tools of the Progress Portfolio to document their data collection. They captured a screenshot of their sound wave, saved it on a Progress Portfolio page, and recorded their measurements using sticky notes and text fields.

Documenting Experimental Trials Only When They "Work"

The planet group, in contrast, experienced more challenges in their data collection activities. This group had decided to investigate Pluto's erratic orbit around the Sun. As described in the introduction to this chapter, their goal was to set up a number of simulations with different arrangements of planets orbiting the Sun to see which had an effect on Pluto's orbit. While both the music and the planet projects involved measuring and comparing, the music group's task consisted of a relatively simple process of analyzing sound graphs. In contrast, the planet group's data collection activity required that they first successfully set up and run a simulation of planetary motion.

The students encountered a lot of difficulty setting up their simulation, however. As we described earlier, setting up planetary motion simulations in Interactive Physics is a non-trivial task. The students were overwhelmed with too many variables to set and no clear notion of which variables were relevant, embarking on a haphazard trial-and-error approach to solving the problem.

There are a number of reflective inquiry issues that should be pointed out here. First, it is not necessarily the case that the students' trial-and-error approach is a bad thing. Indeed, it can be a useful approach to quickly zoom in on relevant variables. However, in order to learn from the trials, the students needed to keep track of what they tried. Students are not accustomed to documenting in this manner. They typically only see a need to write things down when they find the "right answer" or produce something that "works." And, like most people, they tend to overestimate their ability to remember things. This different style of work requires the students to make a conceptual shift in the way they think about what it means to document their work. In this mode of work, "failures" are as important as "successes," and progress towards a goal must be documented, even before the goal is achieved. Moreover, for classroom environments, these "failures" also hold value as a means of demonstrating progress toward a goal. Without such a record, it would be difficult for a teacher to assess how well students performed and in what ways the students had made progress.

Both Laura and the researchers wanted the students to document all of their efforts at getting the simulation to work, including correct and incorrect values and variables. Having this documentation could potentially help the students understand how the different variables do and do not affect the simulation, and eventually help them set up the simulation to test their original question.

The researchers and the teacher tried to instill this reflective inquiry habit in the students by a number of ways. The teacher monitored each group, reviewing and discussing their documentation work throughout the investigation, and reinforcing the affordances of the software by prompting them repeatedly to document their work. Whereas at the beginning of the period, the students did not really understand why or how to document, by the end of the period, through the coordination of the software affordances and teacher prompting, the students started to document their work.

The following example demonstrates this transition in thinking. In this example, the students in the planet group are in their second day of work with the simulation. All of their simulations are resulting in either no movement of the planets, or planets flying away out of their orbits. Over the course of the period, the teacher roved around the classroom helping various student groups, talking with the planet group four times, and each time, she encouraged them to document, getting more and more specific.

At the beginning of the period, the teacher tells the class what they are going to do for the day, and the groups go off to their computers and begin working. About 5 minutes into their work, the teacher comes around to see how the group is doing. The group has been working in the simulation, changing a number of different variables and trying many values (e.g., setting the gravity constant, changing the distance between planets, changing radians setting, etc.). She notices that the students have not written anything down in their notebook, nor do they have the Progress Portfolio open.

Teacher: *How are you guys doing?*

Student: *We're doing fine.*

Teacher: *So are you guys writing down what you're doing? Whether you know what you're doing or not, you need to write down what you do.*

Here the teacher emphasizes that the students need to be documenting their work even if the things that they are trying are not working. One student then asks for a piece of paper from another student, and sets himself up to write things down, but does not actually write anything down.

Ten minutes later, the teacher comes back around. Again, the students have been trying different variables, and have not been successful in getting a planet to orbit the sun. (The names of the students have been changed.)

Teacher: *John, are you writing down things that they're trying?*

John: *I'm trying. I've got two things.*

Teacher: *They've already tried 3 things since I've been here.*

John tries to write more things down, but is confused about what to write.

Twenty minutes later, the teacher returns to the group and has a discussion with the students about the variables that they have been trying. The students are still struggling with trying to get a planet to orbit the sun. In particular, the students are going off in the wrong direction trying to figure out what "radians" are and which value to use in the simulation. The students have only written down a few of the variables they changed on John's piece of paper. The teacher once again brings up the topic of documentation: "Perhaps at least you could write down some of the things you tried today so we could know what you've done? One of the things you could do is to try capturing some things in the Progress Portfolio and writing the results in there."

The students start up the Progress Portfolio and proceed to capture a picture of the current simulation screen. Without any prompting from the teacher or the researchers, one student spontaneously puts a sticky note on the captured screen. He writes: "We tried to plug in numbers to see the earth compared to the moon," and puts an arrow pointing to the earth. (They had previously used the Progress Portfolio with their literature search, and were taught to use sticky notes to point out interesting features on their captured pages).

A few minutes later, the teacher returns to do her end-of-the-day assessment on each group's progress. The teacher goes down her list of rubrics, giving stamps (a rubber stamp on a rubrics page indicating satisfactory completion of the rubric) for the day's work habits. She asks the group, "What measurements have you taken today?" The student points out his notes. The teacher then continues through her rubrics, noting that their measurements were not put into a data table, and giving the students credit for other aspects of their work, but not for their collected data (measurements). In this case, the teacher was looking for evidence that the students documented each run of the simulation and each variable that they changed. Instead, the students have only documented three of their simulation runs. [The key points in the teacher's communication are emphasized.]

> *Are they in a data table? You don't get that one.* Use of class time—you've all been busy, you're writing in your journal, you're keeping the project going. Teamwork can be improved guys. You really need to be working together. I'm going to give it to you for today, but never again if it's like that. Communication, alright. *Alright, so everything but measurements today.* Good job.

The students then continue what they were doing. The student writing down the observations has written: "We tried to plug in numbers to see the earth compared to the moon. We need to find the velocity and the gravity and other variables to plug into the simulation."

The researcher asks the students about which variables they still need to find, prompting the other two students to suggest "the distance between the satellites and planet," "mass of each," and "gravitational pull and formula for gravity," which are all typed into the observations field (see Figure 5).

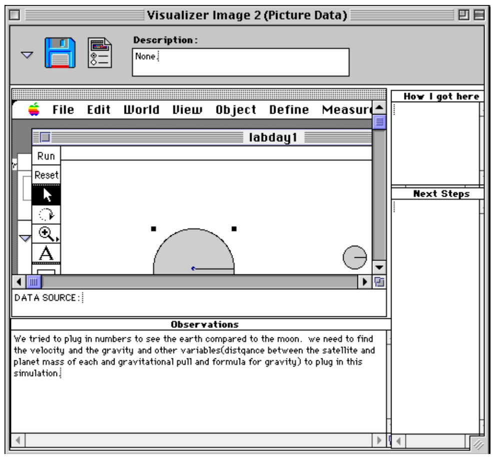

Figure 5. Students capture and annotate their work in the investigation environment (captured from Interactive Physics).

This example illustrates the students' progressive understanding of how to document and why they needed to document. At the beginning of the class, the students clearly did not adopt the documentation task they were expected to do. The teacher had tried to encourage them to document, and they seemed to respond to this directive, but by the middle of the class, it was clear that they did not know what to write down nor how to write it down. Near the end of the class, the teacher gave students a specific strategy for documentation—capture and write the results in the Progress Portfolio. This specific instruction seemed to motivate the students to begin more serious documenting. They began to recognize the value that the teacher had placed on the activity, and had some knowledge of how to do it. So they were beginning to understand how to create a record, and that that record had value in this particular classroom. They did not yet seem to recognize the value inherent in documenting their own investigation process however, as they seemed to be documenting their work primarily in response to the teachers' prompts. At the end of class, the teacher reinforced the value of documenting in her class through her use of end-of-the-day assessments, as she pointedly gave the group only partial credit for their work that day because of their lack of measurements and data tables.

The contrast between the two approaches to documentation can be attributed in part to the different nature of work involved in each groups' data-gathering phase. The different contexts led to very different behaviors and needs. For the music group, their data (e.g., pictures of waves, frequency values, etc.) were obvious and easily collected. They were able to construct an initial plan for collecting data that successfully yielded observations for analysis. In contrast, the things that needed to be documented in the planet group's work were not intuitively obvious to the students and required some extended interventions on the part of the teacher. The teacher needed to emphasize to the students the need to document their steps, even if they were trying different things and not getting the results that they expected. In this instance, the coordination of software affordances, teacher prompting, and assessment rubrics helped encourage students to document. The software made the documentation process easier and more apparent, the teacher prompting told the students when and how to document, and the assessment rubrics helped establish the importance of documenting, providing a motivator to document.

Monitoring

A key purpose for having students document is to help them monitor their own progress. The act of documenting itself can involve monitoring as it requires students to step back from their investigative work, identify particularly important steps in their process, and capture and annotate what they are doing. Do students monitor as they document? Can they use their Progress Portfolio records to monitor their progress? How can a teacher make use of these artifacts to help students monitor?

Laura tried to promote monitoring in a number of ways. Together with the researchers, she designed a page in the Progress Portfolio to encourage reflection and monitoring. As the students collected their data in the Progress Portfolio, their data was saved onto pages that prompt students to note "observations," about the data, as well as "how I got here" and "next steps." These passive prompts nudge students beyond thinking about the immediate activity of data collection to how their data relates to the larger goals of their investigation. But as the previous example demonstrated, passive prompts are also easily ignored, and are only effective when combined with teachers' intervention.

Monitoring and Revising Data Collection Strategies

There is some evidence that the students were doing some monitoring as they were collecting data. As the students in the music group were recording and analyzing the sound waves of the trombone, they were recording two sound waves for each note. In the process of creating a record of their work in the Progress Portfolio, one student noticed that the sound waves they were capturing looked very different from each other, when they should have been the same. This example occurs on the first day of their data collection, as they are still working out their data collection routine.

The students have already recorded and measured the first sound wave graph for one note. A student, Ken, is concerned about not playing the correct note, so he plays the note on the electronic keyboard and tries to match that note on the trombone. Ken then plays the note a second time on the trombone as the other students record the resulting sound wave for their second measurement of the same note, but the graphs of the waves look very different.

Norm: *I think these are different graphs.*
Ron: *Should we use that one?*

Even though the students seem to be capturing the "wrong" data, they keep trying to record the note until they get a graph that looks similar.

Ron: *Amplitude changes based on the volume?*
Norm: *Ken, you sure you doing the same note?*
Ron: *Do 'em back to back.*

Ron tells the students to record both graphs over again because the graphs are coming out so different. Previously they had been recording one note, stopping to make measurements, then recording the second note.

Ron: *(after the second graph is a little off) Do it one more time.*

They do it until the two graphs look very similar.

Norm: *Maybe he was playing the second one louder. Should we, uh ... get rid of this one?*
Ron: *Yeah.*

Students delete their first attempt, and capture the screen for the new graphs.

In this example, the students were monitoring the data that they were documenting, and noticed that the sound waves looked different when they should have looked the same. This seemed to be occurring as they were sampling the same note on separate recording occasions, so there was some variability in how the note was played (both in terms of proximity to the microphone and the intonation). So they revised their data collection strategy to minimize this variability and maximize the "sameness" of the two collected graphs. This example illustrates a strategy of reflective inquiry: monitoring data collection strategies, and revising them when they are not meeting goals.

There were also some missed opportunities for enhancing the investigation. The students were monitoring at the local level of their data collection activities, but missed the opportunity to reflect on the more global level of their investigation question. Their unexpected differences may have helped them understand some properties of sound. They were on the cusp of a more concrete understanding of how graphs of sound waves are related to the sound itself (e.g., Ron: "Amplitude changes based on the volume?"). But they overlooked the significance of this observation and its potential as a way to refocus their inquiry question. Instead of focusing on figuring out why the graphs were different, they tried to minimize the difference. There were two variables causing the differences in the sound waves: the relative sound level of the note (as measured by the proximity to the microphone, and as played by Ken), and the intonation of the note (Ken was playing notes in different octaves at some point, and Ken may not have played the note with the slide in the exact same spot). Both of these variations could lead to the different waveforms they observed, resulting in an interesting investigation into how waveforms differ on different instruments. Not only did they fail to think about the anomaly they observed, they failed to document it, even deleting "bad" data.

One possible explanation for this missed opportunity is that students' knowledge of waveforms simply was not "deep" enough for them to recognize anomalies and interesting patterns. This points to a more general challenge with inquiry projects of this type: they are very complex and may require a relatively deep understanding of the phenomena to pursue these sidetracks successfully. On the other hand, if we could teach students to be careful about documenting their work, including anomalies, then the teacher could potentially discuss these alternative explorations with the students when she reviewed their work.

Teacher Helps Students Evaluate Their Progress and Extend Data Collection

After their initial struggles with establishing a data collection routine, the music group settled into a relatively straightforward process of data-collection and stopped questioning what they were gathering. Although the students were making good progress in their investigation, the teacher noticed that they were becoming too data driven and felt that they needed to be pushed to pursue their investigation in more depth. The following discussion occurs at the end of the first day's data collection. Like the earlier episode with the planet group, the teacher is going around the room at the end of the day assessing student progress with her stamp rubrics. She opens up a few of the student's Progress Portfolio pages and reviews their work for the day. Based on what she sees, she makes some concrete suggestions to the students about their data gathering:

Teacher: *How'd you guys do today?*

Student: *We got three trials done.*

Teacher: *Excellent! Can I do some stamps? You have data...that's good, that's nice...using your class time . . .* [she gives them a stamp] *You have a journal, somewhere where you wrote down what you've done today and...?*

Student: *Yeah, we got all that stuff in uh...*[referring to the Progress Portfolio]

Teacher: *Here? Can I see*? [The teacher opens up the students' Progress Portfolio document and looks at one of the pages that they captured, Figure 6] *. . .It would be really helpful if you start thinking about what...what you have to do with this afterwards. You have three different kinds of peaks, or maybe four different kinds of peaks on here. So you're going to want to figure out what the frequency of all those peaks is.*

Student: *Okay.*

Teacher: *Cause you got at least four different frequencies...I think...Looks like at least four different frequencies in just that note.*

Student: *Okay.*

Teacher: *So you're going to want to figure that out also. You might even want to write that in there. . .In under "next steps": "We need to figure out the frequencies of all four harmonics in this note."*

In response, the student writes: "We have to figure out all four harmonics in the notes," in the "next steps" text field (see Figure 6). After the teacher leaves, the students then seem to ignore her advice. They never get around to measuring the other peaks, although they do go back through the images they captured and put the positions of the trombone slide in the observations box.

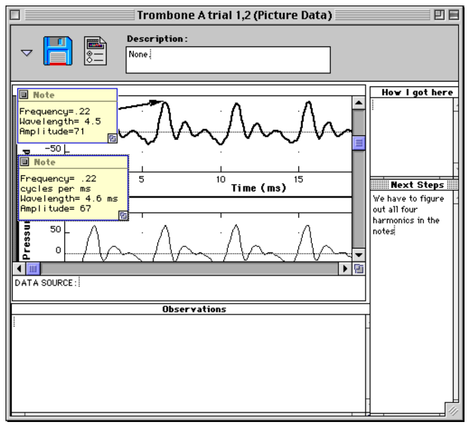

Figure 6. A page showing students documentation of their measurements of sound waves in the Progress Portfolio. The teacher used this to assess the students' progress, suggested some more measurements, and prompted them to record some "next steps."

This episode highlights a number of important instructional strategies. Because the students used the Progress Portfolio to create documentation artifacts, the teacher was able to use these artifacts to review the students' investigation strategies. Student work in the Progress Portfolio created learning opportunities as the teacher reviewed the students' work with them. Rather than merely having access to students' interpreted results, the teacher was able to review the students' raw data and help them reinterpret their data collection methods. Realizing that the students have not explored the data they collected very thoroughly (i.e., measuring the peak of only one wave, instead of all four peaks), she suggested new investigation strategies with the students to help them delve deeper into the data. Measuring the different peaks was the first step towards being able to make more sophisticated comparisons across the instruments. Encouraging the students to measure the peaks of all of the harmonics was the teacher's attempt to get the students thinking about and interpreting the content of what they were doing.

As this example suggests, while students kept track of which things they had recorded and which parts of their plan were pending, they did not assess their progress very thoroughly. The key skill here was knowing or recognizing when they needed to reassess their work process. In some cases, seemingly unresolvable problems—like the planet group's challenges with the simulation—can trigger reassessment. On the other hand, other problems may not trigger reassessment because students are able to continue down their existing inquiry path. So while the music group had some data collection problems (e.g., trying to make sure their samples matched), the problems did not point out the shortcomings of their approach the way they did for the planet group. To get the students to reassess, the teacher had to step in and prompt the students to explore alternatives. The record of work the students had collected in the Progress Portfolio provided the concrete trace of their data collection and interpretation necessary for this conversation.

Our challenge lies in instilling these reassessment strategies in students. They need to be able to recognize and trigger reflection themselves, making reassessment a habit of inquiry. One way to do this is to use the act of creating documentation to trigger reflection by building in more specific reflective prompts. For example, as students capture sound graphs onto their pages, they could be prompted to ask themselves if the wave pattern matched the previous wave pattern. However, as these examples suggest, a more powerful use of the Progress Portfolio is simply its ability to provide the teacher with artifacts with which to diagnose and guide student investigations. Using the Progress Portfolio artifacts, the teacher is able to help the students reinterpret their raw data, talk about their plans for their data, and suggest concrete next steps. In contrast, without the Progress Portfolio artifacts, the teacher would have had to rely on the students' own accounts of their activities.

Communicating

Presentations are an important part of project-based learning. A central aspect of doing research is communicating to others what you have learned. How can the Progress Portfolio facilitate communication between students, and between students and teachers?

Creating Presentations Can be Reflective

The students easily grasped the task of creating a presentation—they understood this mode of communication because they had been exposed to it previously in this class and in other science classes at the school. This ability to create and give presentations, like other school skills, is something that teachers help students develop over the course of the semester and throughout their school careers (Baumgartner & Reiser, 1998).

The task of creating a presentation was very different for our two Progress Portfolio groups. In spite of Laura's efforts, the music group never really progressed beyond collecting and measuring their sound waves. They did not really derive any principles of sound, nor make any generalizations. In the end, their project was primarily focused around data collection, and the act of putting together their presentation reflected this. In creating their presentation, they simply reviewed the sound wave graphs they had collected and put them together onto comparison pages, and added a few literature search pages, a title page, procedure, and a discussion page. The artifacts that they had created throughout their investigation made the task of creating a presentation very simple and effortless (see Figure 6).

In contrast, the main challenge of the planet group was literally reconstructing their investigation, and figuring out how to present an experiment that essentially did not have any conclusive results. By the end of their project, the planet group succeeded in the first of their four experimental trials: getting Pluto to orbit the Sun. Through a mix of trial and error (and help from the teacher and the researchers) the group had figured out that in Interactive Physics simulations (and unlike the real world), planets needed an initial velocity to set them spinning; otherwise, they would be gradually pulled into the sun. The students also worked out a set of values for initial velocity and interplanetary distances that would result in a stable orbit. However, they did not reach a point in their investigation where they could address the effects of other planets on Pluto's orbit. Despite not having an answer to their original question, the teacher was able to help the students understand that they could still create a presentation that focused on what they had discovered about planetary motion.

The planet group began creating their presentation only to discover that they had captured too few images from their many experimental trials, and that deciphering the images they did capture was difficult as they had not documented the variables being explored. So the group's time was spent trying to figure out what these images were, and getting confused about their naming scheme. They had originally set up four different trials in a data table, which they called Trial 1, Trial 2, etc. When they were struggling with the simulation, they would try to set up Trial 1, fail, change something, and call this second trial, "New Trial 1," (They were using the number "1" to refer to their first experiment, which was supposed to explore the Sun's effect on Pluto's orbit, rather than as a numbering scheme for their simulation runs). The following dialogue illustrates the students' initial confusion, and their efforts at reconstructing what they did. The students were paging through their captured screens trying to figure out what they had captured (see Figure 7):

Student 1: *I think this is …*

Student 2: *What is this, is this trial one?*

Student 1: *Oh, this is…where we tried the actual distance but tried to plug in velocity.*

Student 2: *Do you have [trial] four with just distance and masses?*

Student 1: *Yeah, they're in the workspace…*

Student 2: *This was the one where we were trying to decide what initial velocity was needed, right?*

Student 1: *Yeah.*

This example demonstrates the need to document the rationale for decisions along with the interpretation of results. Ultimately, if students adopt a reflective inquiry style of work, they can create a trace of their work that records not only what they did, but why they did it and what they learned from each step.

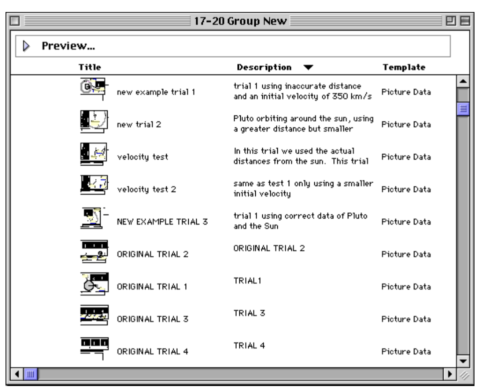

Figure 7. Students review a list of their captured images in the Progress Portfolio workspace to reconstruct what they did in their investigation, and choose images that best convey the tenor of their investigation.

As the planet group created their presentation, they had to reflect on many aspects of their work. As the dialog above suggests, the students had to reconstruct the various trials that they had investigated, noting which variables were changed, why they were changed, and the results of these trials. The students were not starting this reconstruction process from scratch. Although they did have to reconstruct a more complete description of their work, the record of the important steps captured in the Progress Portfolio enabled them to reconstruct the important decisions they made and the different approaches they had tried in order to achieve a working orbital simulation. They had a partial record of their work captured in the Progress Portfolio, so the reconstruction process centered on figuring out the nature of the trials they had captured.

Without the Progress Portfolio, the student group would have had only sparse records of anything they tried beyond what was in their original paper table of values, their meager notes, and their recollections of the trials.

Documenting in Presentation Creation Phase

There is an interesting change from the data collection phase to the presentation creation phase in how the students documented their work. During the data collection phase, the planet group students seemed to focus their documentation around simply recording the values of the variables they were trying. They rarely captured anything, and mostly wrote down things that worked. In contrast, during the presentation creation phase, they were more sophisticated in thinking about what to capture and how to annotate it. The students were careful about setting up the simulation so that it conveyed the essence of the trials, using sticky notes to label the astronomical objects, and writing detailed observations on each page. Rather than simply capturing the screen at the end of a simulation run, the students carefully set up the simulation screen to capture it in a state that best conveyed the results of simulation run. For example, to illustrate the results of one of their trials, they wanted to capture a screenshot that clearly showed that Pluto was about to collide with the sun (see Figure 8). One student tells another student how to capture as they work in the simulation, "I guess we should stop it [the simulation] before it gets to the sun."

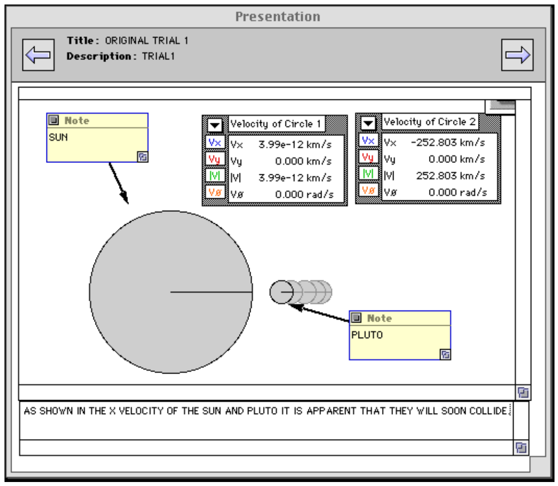

Figure 8. Students re-construct their simulation trial for their presentation. This page shows the result of one of their trials, depicting Pluto moving towards the sun.

In addition to thinking about what their pictorial representation should look like for their presentation, the students also approached their annotations in a more reflective manner. As the students created their presentation pages, they also annotated their pages (using the "observations" field) with notes that suggested an enhanced awareness of their own investigative process, as well as an awareness of conveying ideas to an audience. (These examples were drawn from the written artifacts and from various dialogs in which one student was telling another student what to type. See Figure 9.)

- How to interpret the images: "This is the path that Pluto followed in escaping ..."
- How the trial was set up: "This one was at a greater distance and a less velocity."[Written.]
- Shortcomings in their methodology: "Both new trial one and new trial two have a working orbit, but the actual distances from the sun are off in these trials." [Written.]
- Descriptive interpretations of the trial results: "We believe we have put in a velocity that's too high since the planet seems to have escaped ... the sun's gravitational pull."

- Relating the results to their larger inquiry questions and hypotheses: "We were correct in our theory that the initial velocity would create the right orbit. Correct in our new hypothesis ..."

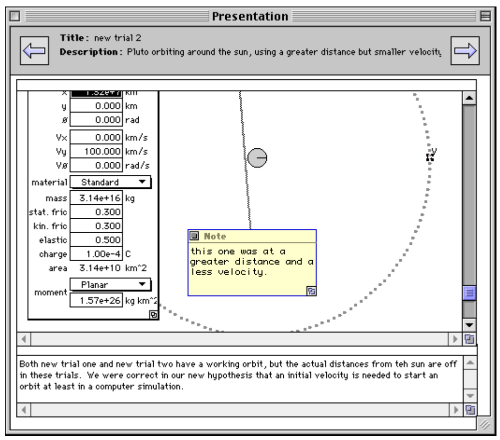

Figure 9. Students add a written explanation of the setup and results of a trial on a presentation page.

This difference in the way they approached documenting could be attributed to several factors. One possible explanation is that the combination of the teacher's constant prompting throughout their project and her use of rubrics that specifically assess documentation has paid off and the students are starting to understand the need to document their work, errors and all. For example, one of the students tells another student as they are putting together their presentation: "Save some where it doesn't work because we need to put some of that in our discussion of results. Go back and save some where it did mess up. These were sort of describing what we did ... Also save like what you inputted for velocity when it got away."

How did they come to this realization? In addition to the teacher's prompting and assessing, the students simply needed to have some concrete artifact to show during their presentation. Since they did not have any successful trials, they needed to show their unsuccessful trials, which the teacher had repeatedly told them was important. Another possible reason is that they better understood the model of work: creating presentation slides is a task that the students understood. They knew what the final product should look like (even if only approximately), they knew who the audience was, and they knew how to create such a product. Annotations describing the graphics were part of their model of this artifact, having been established earlier in their work. As the above examples show, the students also seemed to be more aware of the audience for their annotations. Their annotations took on the character of prose rather than cryptic notes. In contrast, during the data collection phase, the students did not seem to have a clear understanding of what a documented artifact should look like nor what purpose the documentation was supposed to serve. Unlike the data collection phase of work, the nature of the task during the presentation creation phase may have helped the students better understand the need and the purpose of documentation.

One way to look at the creation of the presentation is that documentation and reflection are the central skills that are needed during this phase of the activity. In contrast, during the data collection phases of work, documentation and reflection were ancillary to the central tasks of finding sources and gathering data. So although the students may have understood documentation and reflection better by the time they were creating the presentation, the nature of the task itself may have aided them as much, if not more, than their understanding.

Reflective Conversations During the Presentation

Reflective inquiry was also in evidence during the act of giving the presentation to the whole class. In their presentations, both groups made extensive use of their collection of captured and annotated data images as they explained their inquiry processes. Their presentations featured annotated data from all stages of the investigation, including their literature search, various trials in the simulator or data visualizer, early understandings, and final conclusions. Rather than simply showing "what we found," the students gave an account of how their ideas about their topic changed over the course of their investigation. In comparison to other groups using HyperStudio or Claris Home Page to create their presentations, the Progress Portfolio groups' presentations included more detailed descriptions of investigation trials, and more investigation-based rationale for conclusions.

For example, the planet group used the Progress Portfolio to show a sequence of images captured from four different trials they ran with the physics simulation. A student's introduction of these pages shows evidence of a number of different levels of thinking about their investigation process:

> This one we used, uh, the correct distance, but we used a smaller velocity, uh, we used a one—this is part of our trial and error method—and this one looked like it was going straight into the sun.

Here we see the student using annotated images to:

- Explain inquiry decisions: "This one we used ... the correct distance, but we used a smaller velocity...we used a one [km/s]."
- Characterize their inquiry strategies: "This is part of our trial and error method [for trying out different values to see which one worked]."
- Explain outcomes: "And this one looked like it was going straight into the sun."

The images and annotations captured in the Progress Portfolio also facilitated reflective conversations between the students and the teacher. During the presentation, having detailed images from trials allowed the teacher to have in-depth reflective conversations with the students about the setup of each trial as well as the meaning of their conclusions. For example, on the basis of the four different trials presented by the planet group, the teacher was able to engage the students in a conversation about their findings. As the group presented their data in the Progress Portfolio, their artifacts enabled the teacher to prompt the students to be more specific:

> I know you weren't able to answer your original purpose. If you were to revise, could you state clearly what your original purpose was and what you found out? Can you be more specific than that? … The orbit of what? Any old planet? … I want you to be really specific… What did you find out about the orbit of Pluto? … Our revised purpose is this, our answer is this.

Discussion: Some Reflections on Reflective Inquiry and Its Support

It seems appropriate to end this chapter with some reflections on our own designs and experiences.

Students Show Evidence of Developing Some Reflective Inquiry Skills

This study provides a rich picture of the role of reflective inquiry in students' investigations. Both student groups found this data-rich and project-oriented style of work challenging, and were successful in some ways and not as successful in others. They were both successful in working through the whole inquiry cycle. They were able to generate questions, gather and read background materials, develop a methodology to address their questions, generate and analyze data, and talk coherently about their results. But both groups also had room for improvement. The music group could have benefited from a more refined question, and the planet group had only just gotten to the point in their investigation where they could begin to set up the experiments they had originally planned.

Overall, both groups of students demonstrated some level of facility as reflective inquirers. While they may not have started with a well-developed sense of reflective inquiry, through their work in their investigations, and through the guidance of the teacher and the affordances of the software, they started to develop some reflective inquiry skills. Both groups used the Progress Portfolio to create a record of their work, capturing their data, and annotating the data with some information about its relationship to their work. The act of creating this record helped the students to monitor their own work, and provided learning opportunities as the teacher reviewed and discussed their records with them. By the time the students created a presentation to communicate their work to others, the student groups (especially the planet group) showed evidence that they had progressed in their understanding of how and why creating a record of their progress was important.

It was not necessarily the case that the high achievers (the music group) were able to succeed where the average achievers (the planets group) struggled. The investigation environment being used by the planet group (Interactive Physics) was much more complex and difficult to use than software use by the music group (Sound 3.01). In fact, another group of high achievers in the same class was also using Interactive Physics in their exploration, and they had similar problems. Afterwards, in our conversations with the teacher, she said that the Progress Portfolio "saved" the planet group.

> They had a lot of ideas for how to get Pluto to go around the sun, and none of them worked. But by the end, they could tell a really good story about what variables they tried and how they tried to make it go around and stuff like that, and how they learned about the velocity and the start-

> ing point of Pluto ... and how that helped... They could tell that story really easily ... Where this group couldn't [the non-Progress Portfolio high achievers group] ... They didn't succeed in the experiment, but they learned something about doing experiments.

The music group succeeded in part because they did a good job of establishing a good data collection routine. However, their advanced planning allowed them to fall into "auto-pilot" mode, forging ahead and not really monitoring their progress. In contrast, the planet group was practically forced to monitor their progress as a result of the complexity of the simulation.

Lessons Learned About Promoting Reflective Inquiry

In addition to having a richer picture of what reflective inquiry looks like in a classroom context, we were also able to identify some key leverage points for improving supports to promote reflective inquiry.

Understanding Why and How to Create a Record

Understanding why it is important to create a record of progress, and how to do so, is one of the main challenges that students face as they learn reflective inquiry. The implicit task model provided by the Progress Portfolio's tools is not sufficient to develop reflective documentation skills. Knowing how to document is not just a matter of providing "actions" that a student can take with software tools. Student conceptions of the task, their expectations, their understanding of its purpose, and its intended audience has a great impact on the nature of the work they do. This was very evident in the way that the students approached the task of creating a record.

We were overconfident in assuming that prompting students to write things down would be sufficient. The change in documentation behavior from the data collection phase of work to the presentation phase suggests that the students' conception of the task (especially awareness, purpose, and audience) had a significant impact on the quality of their documentation. During the data collection phase, students were hindered by a model of the task that suggested that "documenting" consisted of writing down what worked, and anything that did not work was not interesting. In the planet group's case, this approach to their work would have led to a failed project. But since the teacher was able to help them shift their task model, to see how they could tell a different story about their investigation that focused on the process of the investigation rather than only the results, they began to see the benefit of documenting all of their work, including "mistakes." This understanding was further developed as the students created their presentation. Their understanding of the product helped them to document in a way that they did not do while collecting data.

Making this shift in their concept of inquiry work is key to getting students to document. This has three potential implications for instructional practice. First, it is likely that understanding this new mode of work requires experiencing the whole cycle of inquiry at least once in order to fully appreciate how each of the components fit together. As students begin to see the value of documenting in the latter stages of their project, they may begin to approach the task of documenting differently. This suggests that reflective inquiry needs to be developed across multiple projects and repeatedly addressed throughout a school year. We have recently begun to explore these more extended implementations in a number of classrooms (Loh, Marshall, Radinsky, Mundt, & Alamar, 1999).

The other implication for instructional practice is that shifting student understanding of the task needs to be an explicit part of a teacher's pedagogical practice. In our original conception of the tool, we had envisioned the teacher's role as primarily that of using the records in the Progress Portfolio as a conversational prop for pedagogical discussions. We did not anticipate how much the teacher would be responsible for setting the expectations of use around the software. How the software was or was not used was determined by the value that the teacher placed on the activity through her use of assessments, and her conversations with students as they worked in their investigation. Teachers need to use examples, rubrics, and explicit teaching strategies that can help students develop an understanding of the value of creating a record.

A third implication for instructional practice is that we need to make data collection strategies an explicit focus for students. In project-based science, it is common to focus on developing a question, forming hypotheses, analyzing data, and communicating results. But documentation itself is also an important component of this process. Students need to learn explicit strategies for documenting, just as they do for the other phases of project work. For example, at the end of each day, a teacher might have students reflect on what they captured and explain why they captured it. Or she might encourage students to share their documentation strategies with others who can point out what is missing.

Problems as an Instigator of Reflection and Monitoring

Helping students to develop the necessary skills for monitoring and reflecting on their investigative process also requires a complex set of instructional strategies. Our basic approach was to put students in a proactive monitoring role. The locus of control for most of these interactions lies with the students, rather than being software- or teacher-driven. Students are designing their own data-gathering strategies. Rather than being given worksheets with tables of numbers to fill in, the students are creating their own tables.

One of the design tradeoffs that we had considered early in our development was concerned with this notion of student control. One might think that the "ideal" inquiry support software would make it as easy as possible for students to make a record of their work, even automatically capturing all aspects of their work in investigation environments. However, because our goal is to have students take on the responsibility of actively monitoring their work, we felt that an important aspect of our design was to give students the responsibility of documenting and annotating their work, rather than doing it completely automatically. This way, students have an opportunity to learn not only how to document, but also to experience the pitfalls of haphazard documentation.

Putting students in control, however, is only a part of the solution. Students also need to recognize when they need to monitor their work, and how to monitor their work. As we said at the beginning of this section, the extensive monitoring that the planet group did was very much driven by their problems with setting up the simulation. This suggests perhaps that one way in which monitoring may lead to revising one's strategies is when there is a perceived problem. Indeed, this was the case with the music group early in their data gathering. Their perception of a problem with the two unmatched graphs of sound waves led them to revise their data collection strategies to record both sound waves at once. In a way, this supports our decision to make the process of creating a record an active, rather than an automatic process, as the act of creating a record can help students recognize problems.

The Process of Creating a Communicative Product is as Important as the Communication Itself in Fostering Reflection

Our original motivation in designing the presentation tool was to help students see the benefits of documenting as they worked, that the artifacts they were collecting along the way had some value in themselves and were not just worksheets to be filled out. We also thought that a presentation would really help facilitate communication among students and teachers. We did not really anticipate how much reflection would be promoted by the act of putting together the presentation. Creating a presentation turned out to be a very reflective process wherein students needed to reconstruct an investigation and make decisions about how to tell a coherent story, abstracting from the details. An awareness of the potential audience really seemed to help students to develop a much more coherent product.

There are some obvious implications for instructional practice. First, presentations can be as important to inquiry as the experiment itself. Presentations are often tacked on to the end of projects as an afterthought. Our experience suggests that the process of creating a presentation can be a powerful learning experience, helping students to develop a better understanding of the scientific process as a whole. Second, we may want to consider instituting multiple iterations of presentations in a project cycle. For example, students might be asked to present their project proposal, or their data collection strategies. This can potentially provide more opportunities for reflection throughout the project. This also has the added benefit of helping to establish a reflective task model earlier in the project's life cycle.

Final Remarks

Students do not learn to be reflective inquirers within the scope of a single project. Rather, students need to develop the habits and dispositions of reflective inquiry over time. The students in this study at first did not really understand how to create a record, monitor, and communicate about their work, nor really understood its purpose. But as the teacher guided the students through their project, and as the students began experiencing the need for and the benefits of their reflective practices, we saw evidence that they began to develop some of these skills, to internalize the habits of reflective inquiry. Reflective inquiry did not consist of disparate skills that students learned piecemeal. Rather, learning to be a reflective inquirer depended on the interaction of all of the components of reflective inquiry in the context of an authentic problem. Students documented in order to have something with which to monitor and review their work, and to have something to communicate about. Also, as we saw in the examples, the processes of monitoring and communicating (and creating communicative products) prompted students to document in more sophisticated ways.

Promoting reflective inquiry requires this confluence of multiple streams of instructional strategies: from the affordances of the software, to the rubrics that are used to guide student work, to the verbal prompts provided by teachers. Having tools that enable documentation is helpful, but not enough. Making the tasks explicit is also helpful, as is providing examples, and tying performance to grading rubrics. Instilling this mode of work requires giving specific prompts when students are in a position to act upon them, and more importantly, to provide students with the opportunity to reflect on what they did so that they can see the direct benefit that this reflective inquiry mode of work provides. It requires a long process of building skills, changing understanding of the nature of the task, repeated prompting and application of the skills in various contexts. It requires breaking many existing school habits that interfere with reflection, and acquiring new habits that encourage the thoughtful pursuit of investigations.

The Progress Portfolio was designed to support this process by making it easy for students to create artifacts that can represent their work processes and be used as objects for reflection. The tools help students to make the inquiry process itself visible so that they can review it and talk about it. Our pilot study has offered evidence that teachers can effectively use the tool to promote aspects of reflective inquiry, and that students can benefit from its use. Our current work now takes a longer developmental view of reflective inquiry, expanding reflective supports beyond a single project to explore the role of reflective inquiry across multiple projects throughout a school year.

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