The Progress Portfolio: Promoting Reflective Inquiry in Complex Investigation Environments

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Abstract

Scientific inquiry in complex data-rich environments is a goal of much educational reform, but students require supports to manage the complexity of such investigations. We propose an approach to providing this support by making the processes and products of an investigation into explicit objects for reflection. We describe design research exploring ways to promote *reflective inquiry* among middle-school and high-school science students. We outline obstacles facing students in conducting investigations and give an overview of the design principles for our inquiry-support software environment, the Progress Portfolio. The specific tools provided by the Progress Portfolio for capturing, annotating, organizing, and presenting data are described in detail. We conclude with a discussion of pilot studies conducted with middle-school and high-school students.

Keywords — design and interface issues, instructional strategies and approaches, tools for open-ended learning

1. The Need for Support for Reflective Inquiry

Much current research in science education focuses on engaging students in collaborative scientific inquiry projects: working in small groups to formulate researchable questions, design investigations, gather and interpret data, and communicate results to groupmates, classmates and teachers (Linn, Songer, & Eylon, 1996) . To provide opportunities for authentic classroom science investigations, curriculum and technology developers have designed a variety of software and learning activities which immerse students in data-rich environments and provide them with complex tools. These new roles and technological tools for students are a focus of reform efforts in science education (NRC, 1996) , yet this vision of project work remains unachieved for many students (O'Sullivan, Reese, & Mazzeo, 1997) . There are two sets of problems students face: coordinating inquiry processes, and managing complex information.

1.1. Problems with coordinating inquiry processes

The complexity of open-ended investigations poses difficulties for groups of students who must continually negotiate plans and share understandings throughout an investigation. Students differ greatly in their ability to be planful and organized in working through a complex space (Shute, Glaser, & Raghavan, 1989) . Classroom investigations are often plagued by unnecessary repetition, prolonged tangents, and incomplete results (Kuhn, Schauble, & Garcia-Mila, 1992; Schauble, 1990) . Individual students often have difficulty communicating results of their exploration to groupmates. Students have difficulty differentiating between hypotheses and evidence, and coordinating the two in interpreting investigation results (Kuhn, 1989) . As students explore they lose their place in the inquiry, failing to realize possible connections and leaving important questions unresolved. Students may need to look back at earlier data to make sense of a current analysis or realize its significance. They may generate many analyses, which may be unwieldy to keep in mind or reconstruct. Yet students are unlikely to note or store data whose immediate relevance is not clear, or to have recorded how they generated analyses or what they found important about results.

1.2. Problems with managing complex information

The introduction of information-rich computer environments presents additional problems.

These classes of investigation tools include data visualization software (e.g. ClimateWatcher, Northwestern University; EarthView Explorer, Columbia University), simulation environments (e.g. GenScope, BBN; Interactive Physics, Knowledge Revolution), web browsers, and digital libraries of text, images and video files. These software tools enable students to query complex data sets, to generate their own data sets, to construct visualizations representing complex phenomena, and to set up and run their own simulations to isolate variables and explore relationships. They also create new demands for skills in managing complexity. While students may be able to interpret the meaning of one image, they are also able to easily call up another, quickly losing track of their original plans and interpretations. Collaboration among students and communication of results requires joint attention to detailed visual data and discussion of complex relationships, which is often unsupported in classroom interactions. Finally, complex investigations may require combining data and interpretations gathered from several environments, such as images from a visualization environment and images or text from other information resources like the world wide web.

1.3. Need for reflective inquiry

Powerful tools and information-rich environments are not sufficient to promote successful collaborative inquiry. Together, students need to learn how to organize, evaluate, communicate about, and monitor the activities of an investigation. Students must negotiate shared inquiry plans and candidate explanations, systematically interpreting and discussing the data obtained. Students need to periodically reflect, evaluate their progress, coordinate shared understandings among group members, and replan. To be more successful, students must develop the skills and habits of *reflective inquiry*.

1.4 Prior research on supporting reflective inquiry

Reflection, in the sense of stepping back from activity to view actions, objects, system states, or emerging understandings from a temporarily changed perspective, is widely cited as an essential component of authentic scientific investigation. Research suggests three broad categories of reflective cognitive abilities that are required for conducting successful scientific investigations:

(1) *self-monitoring*, in terms of strategic planning, reflecting on strategies used, and evaluating outcomes of using strategies (Collins & Brown, 1988; Davis, 1996; Schauble, Glaser, Raghavan, & Reiner, 1991; Schoenfeld, 1987) ;

(2) *maintaining 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) ; and

(3) *developing reflective reasoning and argumentation skills* involving coordination of questions, beliefs, and observations (Klahr & Dunbar, 1988; Kuhn, 1989) .

Software support for developing these reflective inquiry abilities falls mainly into two categories: self-contained, content-embedded investigation environments with reflective supports built in (Schauble, et al., 1993; Shute & Glaser, 1990) ; and content-neutral communicative structures designed to promote reflection (Edelson & O'Neill, 1994; Scardamalia, Bereiter, McLean, Swallow, & Woodruff, 1989) . While the former class of software affords content-specific prompting and meaningful representation of student actions by the system, the latter allows for more flexibility in terms of what type of investigation can be supported (i.e. support for more than one domain).

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, perhaps comparing it with other solutions. For example Schauble's (1993) DARN system provides software artifacts that show students a visual representation of their investigation strategies, which can be used by students to reflect on their work and plan their next steps. Similarly, Collins and Brown (1988) describe the role of computer artifacts in reifying the learner's actions so that they can become objects for reflection.

The work described here builds upon this body of prior work by providing an investigation-general support tool which works in close integration with almost any other software environment, providing the kind of meaningful trace of inquiry artifacts afforded by micro-world environments, while also providing the flexibility of the content-neutral structures. This enables not only prompts for reflection after an investigation, but also an infrastructure for recording products and factoring the result of reflection into the ongoing investigation.

2. Supporting Reflective Inquiry with the Progress Portfolio

Our research explores the design of learning environments to promote reflective inquiry, not by creating stand-alone investigation software, but by providing software tools and supports which can be used by students conducting inquiry using any computer environment. The core of our approach is finding ways to promote reflection and discussion around the often-invisible processes and intermediate products of inquiry by making those processes and products concrete. This involves prompting students to make their questions and understandings explicit, and providing visible representations of inquiry activities and processes for students to inspect.

Our approach to promoting reflective inquiry is embodied in a computer-based inquiry support tool, the Progress Portfolio. The Progress Portfolio is designed to afford reflective actions in the context of image-intensive investigation in software environments such as visualizers, simulations, or browsers. This includes enabling the student to record states of the investigation software as images, attach records of their thinking to those data images as annotations, and manage their collections of data images as they accumulate. This functionality turns the transient states of investigative processes into explicit objects for reflection, and enables students to invest those objects with additional meaning. By affording reflective consideration of data objects and organization of these objects in the workspace, the Progress Portfolio is designed to scaffold students in building the skills required for managing complexity.

The Progress Portfolio provides tight integration of a reflective workspace with the ongoing activity in the investigation environment. Our software operates in parallel with any other software environment, and allows the capture of images from the investigation software into the Progress Portfolio: the investigation environment provides a setting for content-based exploration, and the Progress Portfolio provides a setting for reflective inquiry management. We believe students can easily alternate between these modes of activity, without losing the context of their research or the sense of immersion in the investigation environment. At times students may choose to stay focused on working in the investigation environment, pausing occasionally to capture an image and move on; at other times they may choose to work mainly within the Progress Portfolio workspace, annotating captured images, organizing their collection of pages, or creating a presentation from their database, pausing occasionally to return to the investigation software to answer a question.

The basic structural unit of the Progress Portfolio is the *page* (see Figure 1), which can contain one or more *data images*, written or drawn *annotations* on and around the data images, and *text entry fields*. As students work through an investigation, they may accumulate a large number of pages, which can be organized into *clusters* in the Progress Portfolio and viewed as a chronologically- or thematically-organized *trace* of the investigation. Pre-structured page types, or *templates*, can be constructed by the teacher, activity designer, or students, to support activities and data specific to a particular kind of project.

In the following section we describe these features of the Progress Portfolio in more detail, highlighting the specific ways they are used at

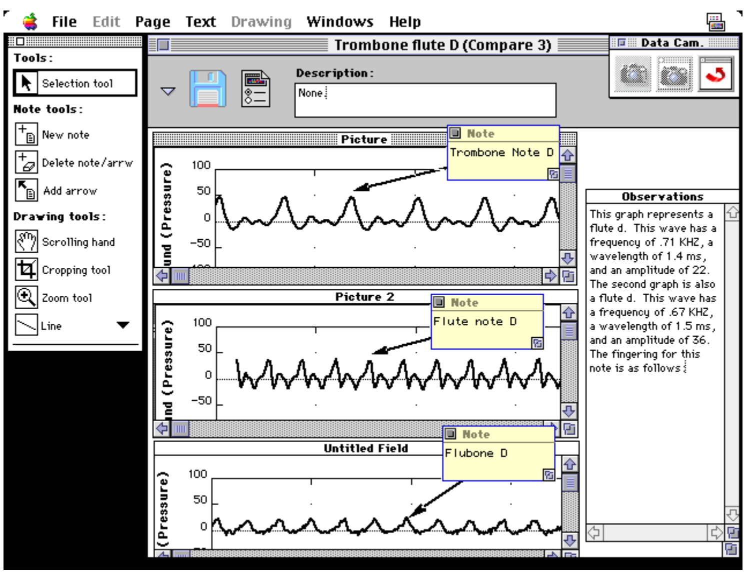

FIGURE 1. This is a Progress Portfolio page created by students to compare three captured data images from a visualization environment (Sound 3.0.1) using a template of their own design. The students have annotated their data sources and recorded their thinking in the "Observations" text entry field.

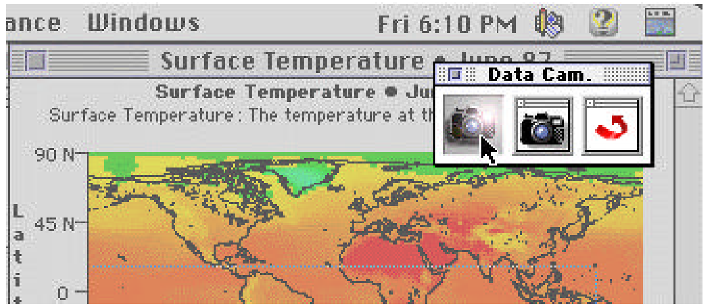

FIGURE 2. Clicking on the Data Camera will capture an image and save it to the Progress Portfolio. Here, a student captures a temperature map from an earth sciences visualization environment (Climate Watcher).

each phase of the investigation process: formulating research questions, gathering data, recording observations, analyzing and synthesizing, and communicating results.

3. Promoting Reflective Inquiry Throughout the Investigation

3.1. Formulating research questions: Customized Prompts

One of the key functions of the Progress Portfolio is encouraging students to make their questions and interpretations explicit by writing them down. The Progress Portfolio provides *text entry fields* that are customizable by the instructor to prompt students to record their thoughts. For example, a teacher can create fields with prompts like “What is the topic you want to explore?” and “Write down 10 questions that you have about your topic.” Thus a group of students might start their investigation by gathering around the Progress Portfolio and brainstorming questions they have about their topic, discussing possible lines of research, and recording their candidate questions. The teacher can then discuss these various possibilities with the students, negotiating a research question that students then record on a Research Question page. These pages can be revisited throughout the investigation, allowing students to further revise their research questions as they work. Revisions to the Research Question page provide a record of changes in research focus over time, which may later become the organizing structure for a presentation on the history of the investigation.

3.2. Collecting data: the Data Camera

As students explore an investigation environment, they generate a succession of images rich with information which may have bearing on their research questions. The first reflective step toward investing these images with meaning is the decision to capture an image, thus turning a transient state of a software environment into a persistent data object. The Progress Portfolio provides a data collection tool called the *Data Camera*, which is always accessible in other applications. Students can capture an image from the investigation environment by clicking on the Data Camera (see Figure 2). The Data Camera takes a picture of the current investigation environment screen and that image is stored on a new Progress Portfolio page. The image can then be resized, annotated, or drawn upon and becomes a part of the collection of pages documenting an investigation.

3.3. Recording observations: Annotation Tools

Students typically do not note how data was generated, in what context, or what it was understood to mean. The Progress Portfolio provides *annotation tools* which allow students to record their observations and reflections directly upon the data objects, in text or drawn graphics. For example, graphs are a staple of many investigations, but the results being displayed in graphs can be ambiguous and open to irrelevant interpretations. Annotation tools allow students to make notes and record their interpretations directly on top of the graph itself, pointing out key features. These annotations provide students with a record of their thinking about the data. These objects can prompt later reflection, as students plan their investigation and discuss their progress with other students or teachers.

One of the annotation features is the *note tool*, which students can use to affix a “sticky” note to pages. These notes can have arrows that can be used to highlight important features of a page or data image (see Figure 3). Notes can also have different labels to serve specific investigative purposes, such as a "Question" note, or an "Evidence of..." note. These customizable note types can be used by teachers or students to meet the needs of a particular investigation. For example, students collaborating in a group might use note-type labels to distinguish among authors when there are conflicting interpretations or labor is divided (e.g. Javier might use purple "Javier" notes, and

Tanisha use blue "Tanisha" notes). In addition, students can annotate images graphically, using a range of *drawing tools*. Colors of drawn lines can also be customized by students or teachers to have particular significance, e.g. red lines can be used to denote presumed tectonic plate boundaries on an earthquake data visualization map.

3.4. Analyzing and synthesizing: Relational Tools

A higher level of reflection is required for making sense of the investigation by exploring the relationships among pieces of data or examining one's own actions in the investigation itself. To promote these forms of reflection, the Progress Portfolio provides structures which encourage students to look at their work from different perspectives, stepping back from the particular items of data to evaluate the larger picture of the investigation, and to organize and reorganize their data to reflect their emerging understandings. These organizations can become part of students' reporting of the history and argument structure of their investigation.

Comparisons:

One way of reflecting upon the significance of data is to make comparisons between data objects, such as simulations or visualizations that represent different variable combinations, in order to draw relationships and generalizations. Comparison pages display two or more images side by side, allowing students to compare and contrast different pieces of data, annotating multiple images to point out comparisons (see Figure 3).

Clusters:

As pages accumulate in the Progress Portfolio workspace, students can move groups of pages into clusters. Grouping data objects into clusters give students the opportunity to organize their data by themes, experimental trials, or other organizational schemes in order to manage the richness of the investigation (e.g. students can put all temperature maps into one cluster, and elevation maps into another cluster). Organizing structures like Pages and Clusters help to decompose the task of information management into understandable subtasks for students: by capturing the fleeting states of investigation environments as manipulable objects, the Portfolio scaffolds the task of reconsidering and sorting sets of information.

Chronological traces:

By prompting students to record a large number of intermediate products of the investigation and to attach their understandings to them, the Progress Portfolio enables students and teachers to study a history of the investigation itself. Chronological traces provide students with representations of their actions in the investigation, enabling them to reflect on their own problem-solving behavior. Students can review the sequence of images they have captured and pages they have created, to reconstruct the reasoning that led their investigation in a particular direction. Annotations provide explicit evidence of what they were thinking in association with each image, and so the trace also gives a history of their understanding to be reflected upon.

3.5. Communicating results: Presentation Mode

The kind of reflective behavior described above, such as students analyzing their own inquiry strategies, must be prompted by curricular activity structures. Left to themselves, students tend to be final-product-driven, and may not spend much time reflecting on their investigative process and strategies. Creating a final communicative product—e.g. a written report, a poster, or an oral presentation—can encourage students to review their investigation. Also,

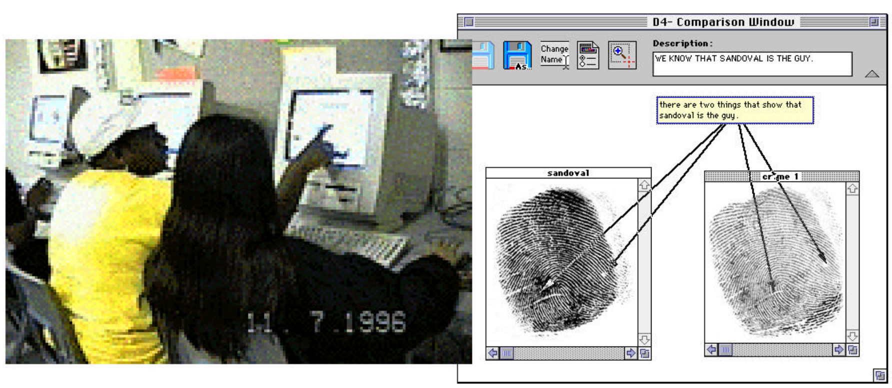

FIGURE 3. Students compare and annotate fingerprint images in a "Crime Scene" investigation. The arrows are pointing to features that provide evidence that the two fingerprints belong to the same person.

communicating results is an integral part of doing science, and often helps researchers come to a better understanding and gain insights into their own work.

The Progress Portfolio supports communication in two ways. First, it can serve as a repository and history of the investigation process, so that as students work on creating their communicative product, they can review and reflect on the record of their investigation—the questions that were asked, the data gathered, the interpretations, changing questions, and understandings, etc.— to generate a story or argument about their results. In this sense, the information that the students have recorded in the Progress Portfolio serves the purpose of notecards, pictures, or outlines that students use to create a final communicative product. Second, the Progress Portfolio provides explicit support for creating presentations with a *presentation mode* in which students can easily port pages from the Portfolio into a simple slide viewer. Both communication modes prompt students to reflect by revisiting the history of their investigation to make decisions about which aspects of their investigation tell the best story. The process of preparing a communicative product becomes the process of organizing a history of the investigation, thereby promoting reflection on inquiry processes within the context of a presentation.

4. Pilot tests with middle and high school students

We have pilot-tested the Progress Portfolio with middle-school and high-school students conducting a range of inquiry activities using several different investigation environments. Early usability studies with middle-school students in an urban setting used a prototype version of the software in conjunction with a web browser, a data visualizer, and a digital library. Five students participated in our informal after-school program, meeting once a week for a period of 6 weeks. Each session focused around a Progress Portfolio activity ranging from creating reviews of world wide web pages to comparing fingerprints taken from a "crime scene" to exploring maps of world populations. Researchers worked closely with each of the students, helping them with basic computer skills (e.g. window management) and Progress Portfolio skills (e.g. how to make a note). These studies showed that the capture and annotation tools were usable by students as

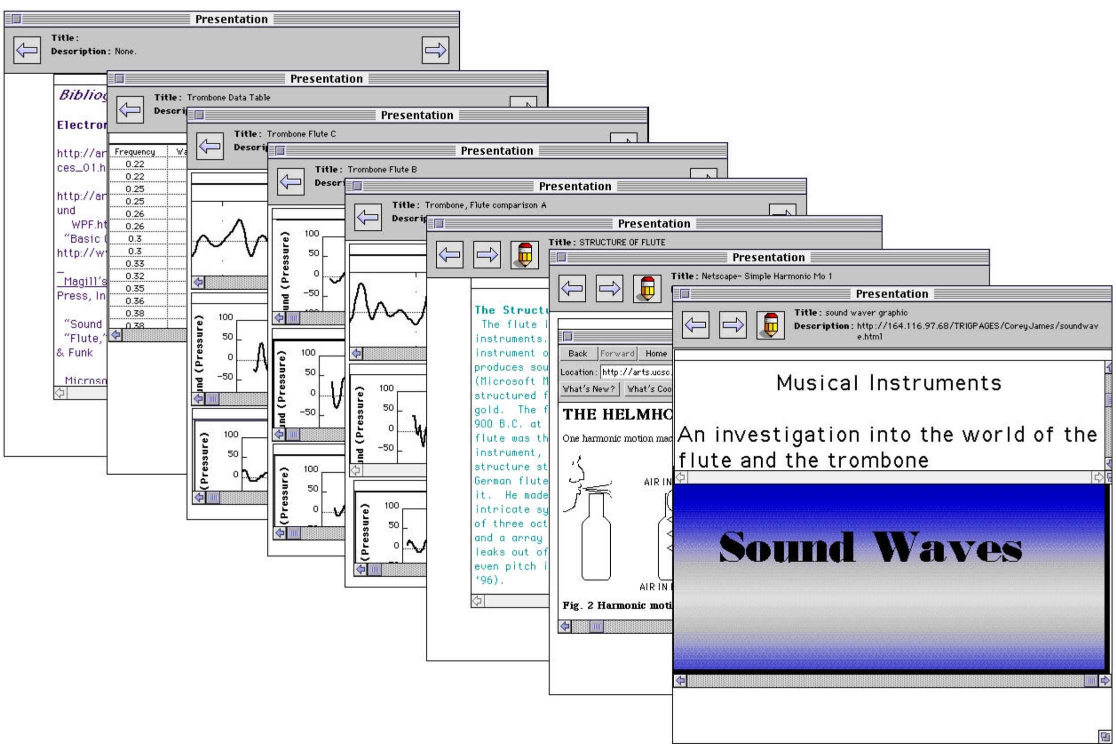

FIGURE 4. Students built these slides for their oral presentation by reviewing their collection of captured and annotated data, selecting the images that best document their investigation, reformatting them for presentation purposes, and organizing them to tell their story.

young as seventh grade. Students worked together, discussing and documenting their findings from various one-to-two-hour investigation activities in the Progress Portfolio. Observations from these prototype studies led to a redesign of several aspects of the interface for improved usability, in particular, making the functionality of the tools more apparent (e.g. we added labels to the tool palette because students were not necessarily familiar with standard tool icons such as a magnifying glass for zooming).

A second pilot test of the software was conducted April - June 1997 with students in two physics classes at a suburban high school. Two groups of students used the Progress Portfolio over a period of six weeks as a part of their year-end physics research project. This project was composed of four main phases of activity: a literature search, a computer-based physics investigation, an oral presentation, and a final written report.

Students used the Progress Portfolio in conjunction with various investigation software provided by the teacher. One of the two groups (2 seniors and 1 junior) used the Progress Portfolio with a simulation environment, *Interactive Physics*, to investigate the nature of Pluto's chaotic orbit around the sun. The other group (2 seniors and 2 juniors) used the Progress Portfolio with a sound wave visualizer, *Sound 3.0.1*, to document relationships between the sounds of notes played on two instruments and their wave patterns, and to support the design of a novel instrument.

Students in both groups used the Progress Portfolio to document the processes of their investigations, gather and annotate data from their respective investigation environments, organize these data throughout the investigation, and create final presentations of their projects for their classmates. Groups not using the Progress Portfolio (there were 3 or 4 groups per class that did not use it) conducted similar projects in these and other investigation environments, and created their final presentations using other software applications: either HyperStudio, a HyperCard-like hypermedia authoring environment, or Claris Home Page, an HTML editor.

One or two researchers were always present with the students as they worked on the Progress Portfolio in the early phases of the project, showing them how to use the tool, assisting when requested, and occasionally prompting students with questions about their project. The majority of this guidance was focused around the use of the tool. The teacher provided most of the guidance for the direction and scope of the investigation itself. In the later stages of project work, the researchers were outside of the room for some sessions as the students worked, but still available for guidance as needed.

All sessions with the Progress Portfolio were videotaped, with a direct-feed from the students' computer monitor to videotape and a microphone placed in the room to capture student and researcher conversations. In addition, the final presentations of all groups (Progress Portfolio and non-Progress Portfolio) were videotaped, and an exit interview was conducted with the two student groups.

In general, the students reported in the interview that the Progress Portfolio was easy to learn and use. All of the students had had extensive previous computer experience, though mostly with IBM-compatibles rather than Macintoshes. Most students also had computers at home. This familiarity with computers simplified the task of teaching the students how to use the software, as students were already familiar with many standard interface features. The computer-based literature search at the beginning of the project also provided an ideal opportunity for students to begin learning to use the basic tools of the Progress Portfolio with a familiar task. This relatively simple task of collecting data was ideal for introducing students to the Progress Portfolio, capturing and annotating data from CD-ROMs and Netscape searches, so that by the time the students were conducting their experiments, they were already familiar with most of the features of the software.

A thorough analysis of our pilot study will be presented elsewhere (Loh, Radinsky, Reiser, Edelson, & Gomez, 1997a; Loh, Radinsky, Russell, Gomez, Reiser, & Edelson, 1997b) , but in general, based on evidence from our observations and videotapes of the students' work and presentations, we found that the students successfully integrated use of the Progress Portfolio into investigations with other environments. The students were able to use the capture and annotation tools provided by the Progress Portfolio to complete their projects, and were able to maneuver between the Portfolio workspace and the investigation environments regularly and without difficulty[1] .

We saw several suggestions of the Progress Portfolio's functionality prompting reflection on inquiry actions, particularly in students' preparation for reporting on their investigation to

[1] This version of the software was not yet robust enough to consistently support clustering, so we did not have the students use those features.

the class. For example, in preparing a presentation, students in the Planets group realized that they needed more images to document the story of their investigation, so they went back to the simulation environment to create and capture more images, discussing what simulation state would best represent their trial and findings. Students annotated data as they were collecting it, recording numerical information as well as their observations. Students grasped the utility of templates in structuring their data gathering and analysis, applying and extending the tools. For example, students in the Music group wanted to structure their data to compare three images of sound waves on the same page, and created a new template to do so (see Figure 1).

During the presentation phase of the projects, the Progress Portfolio groups made extensive use of their collection of captured and annotated data images to present their inquiry processes to the class. Their presentations featured annotated data from all stages of the investigation, including literature search pages, various trials in the simulator or data visualizer, early understandings, and final conclusions. Rather than simply showing "what we found," they gave an account of how their ideas about the domain changed over the course of their investigation. In comparison with other groups using HyperStudio or Claris Home Page, their presentations included more detailed descriptions of investigation trials, and investigation-based rationale for conclusions.

For example, the "Planets" group using the Progress Portfolio showed a sequence of images captured from 4 different trials they ran with the physics simulation. The student's introduction of these Progress Portfolio pages shows evidence of a number of different uses of annotated images for explanation:

> *"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.*").

Non-Progress Portfolio groups often read their conclusions directly from their written report. Anecdotal reports from students suggest that these groups actually spent more time than the Progress Portfolio groups in preparing their presentations, yet much of this time was spent on visual formatting (e.g. colors, sounds, page backgrounds). In contrast, the two groups which used the Progress Portfolio were able to quickly create presentations that communicated more information about both the processes and products of their investigations.

The images and annotations captured in the Progress Portfolio also facilitated reflective conversations between the students and the teacher. Throughout the project, the teacher was able to refer to the artifacts and tools of the Progress Portfolio in asking the students to "*Show me what you got*," and then discussing their progress with them and suggesting investigation strategies (e.g. "*You should be writing this down*.").

During the presentation phase, 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 4 different trials presented by the Planets group, the teacher was able to engage the students in an extended dialogue about the meaning of their findings, helping them to more explicitly specify the generalizability of their results.

By the end of their projects, students seemed to have evolved a more robust understanding of the Progress Portfolio tools, which suggests that students may be able to take fuller advantage of the tools if given more opportunities for conducting investigations with the Progress Portfolio. Further study is needed with students using the Progress Portfolio on more than one investigation to see how students' evolving model of use for the Progress Portfolio changes the ways in which they use the tools as well as the ways in which they reflect on their work over the course of inquiry. Also, we are investigating both teacher and student strategies to facilitate more reflective conversations throughout the inquiry process.

5. Conclusions

The Progress Portfolio software is designed to encourage students to become reflective inquirers by focusing them on the normally invisible aspects of the process of inquiry. Students using the Progress Portfolio document the investigative process, their thoughts, and their interpretations, bringing these features of investigations into the classroom discourse, both within student groups and between students and teachers. The work described here suggests that the approach of building supports for reflection into a wrap-around inquiry-support framework holds promise as a means of impacting students' inquiry strategies and habits. The Progress Portfolio has been shown to have the flexibility to be integrated into existing classroom inquiry activities, and to be useful for students working in a wide range of investigation software. The Progress Portfolio enabled discussion around inquiry products and processes, supporting the collaborative construction of explanations of an investigation. It has also been shown to integrate well into the process of creating presentations. Our future research will focus on discovering principles for designing inquiry activities which encourage students to make use of the tools provided by the Progress Portfolio, and to better understand the kinds of annotation and data storage that will be most valuable to students.

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