Revised 3/25/00

BGuILE: Strategic and Conceptual Scaffolds for Scientific Inquiry in Biology Classrooms[*]

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1. Ambitious Science Learning for Classrooms

The current focus of much work in science education reform is to bring more ambitious science into classrooms. Education reformers argue that students need to learn more rigorous scientific content than what is typically taught (AAAS, 1990). In addition, reformers are attempting to bring more of the practices of scientific inquiry into student learning activities (NRC, 1996). This means establishing a learning setting in which students can take ownership of the questions they pursue, can design and implement an investigation to pursue their questions, and interpret and communicate their results to others (Linn, diSessa, Pea, & Songer, 1994). These goals have emerged from research documenting the shallow level of understanding engendered in what is argued to be a decontextualized approach to teaching science.

In our view, meeting these science learning goals requires helping students make the connection between inquiry processes and the products that result from inquiry, such as theories, models, and explanations. While there is often debate that reform science efforts focus too much on process at the cost of students learning scientific content, we argue that this debate is misguided. Developing a deep understanding of science entails understanding the nature of scientific explanations, as well as the practices used to generate and evaluate those explanations. We argue that the most effective way to teach these scientific practices is to ground students' use of them within their learning about the specific theoretical frameworks of particular scientific disciplines. In other words, effective learning of scientific investigation processes requires using the structure of particular scientific frameworks, such as the theory of natural selection or the framework of behavioral ecology, to tailor strategies for investigation, including framing questions, formulating hypotheses, constructing comparisons in data, and evaluating hypotheses. In order to learn scientific processes, students need to understand how the general strategies of science (controlling variables, discriminating hypotheses) are realized within particular scientific domains. A rigorous understanding of science entails recognizing that theoretical frameworks of scientific disciplines may require different investigation methods.

Acquiring this understanding requires engaging in rich investigations. Yet creating these learning opportunities for students presents two types of challenges: cognitive complexity and classroom culture. First, engaging in

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This chapter will appear in S. M. Carver & D. Klahr (Eds.), (2001). *Cognition and instruction: Twenty-five years of progress*. Mahwah, NJ: Erlbaum.

sustained investigations requires investigation strategies and an understanding of scientific epistemology that poses challenges for students (Carey, Evans, Honda, Jay, & Unger, 1989; Klahr & Dunbar, 1988; Kuhn, Schauble, & Garcia-Mila, 1992; Schauble, 1990; Schauble, Glaser, Duschl, Schulze, & John, 1995). A second obstacle is the existing culture of the science classroom, which is most typically focused on the transmission of knowledge, where the subject matter is presented as solved problems codified as terminology, theories, and laboratory techniques (Lemke, 1990). The epistemology of science that emerges is one of fixed and unchanging “right answers”(Songer & Linn, 1991). Students’ views of science learning lead to strategies appropriate for the acquisition of facts rather than constructive argumentation and reflective inquiry.

To create inquiry classrooms in which students learn through investigation requires basic changes in *the rules of the game* for science classrooms – new curricula and tools must be accompanied by new teaching approaches and an explicit attention to shifting students’ attitudes toward science and science learning. Engaging students in this type of learning requires different values and expectations. It requires creating a different type of classroom culture (Brown & Campione, 1994; Crawford, Krajcik, & Marx, 1999; Duschl, 1990).

To overcome these obstacles requires two complementary forms of support: (1) support for scientific practice, and (2) creation of a classroom culture of inquiry. Support for scientific practices is needed to help students develop the content knowledge required to raise questions and negotiate novel problems in the domain, plan and pursue systematic analyses of complex datasets, synthesize these findings into well supported cogent explanations, and reflect on the implications of these findings for understanding key scientific topics. Creating a classroom culture of inquiry consists of communicating and establishing a culture that sets knowledge construction and the evaluation of knowledge claims in light of empirical evidence as the primary goals of classroom work.

One strategy for reform utilizes new technologies to expand the learning opportunities for students (Means, 1994; PCAST, 1997). Technological tools can provide a venue for rich investigations, providing both access to data and powerful analytical tools. Such tools can provide scaffolding to support scientific practice and can be integral in new classroom inquiry practices. To be effective, use of these tools must be embedded in *technology-infused curricula*, that contain articulated problem contexts, tools, and resources so that students can work through investigations crafted to engage them in the target learning outcomes.

In this chapter, we describe our approach for supporting ambitious science in classrooms. Our work focuses in particular on designing learning environments for students engaged in scientific investigation and explanation of biological phenomena. In this project, called BGuILE, *Biology Guided Inquiry Learning Environments*, we have been developing and studying the use of technological and curricular supports for the teaching and learning of biology. BGuILE technology-infused curricular units center on investigation activities in which students construct empirically-supported explanations from a rich base of primary data. These investigations are made possible through software environments that serve as the investigation context, provide access to the primary data, and provide support tools for analyzing the data and synthesizing explanations. Activities preceding investigations are designed to help students build the rudimentary knowledge and skills that facilitate a thoughtful and thorough treatment of the problem investigations. In addition, informal and structured discussions are interspersed throughout all the activities in order to provide opportunities for reflection and for sharing and critiquing ideas.

We begin by describing our approach to supporting student inquiry. We then describe the design principles for technology-infused curricula that have emerged from this research. We illustrate these principles with particular curricula and tools that we have developed for courses on evolution, ecosystems, and behavioral ecology at the high school and middle school levels. Finally, we overview the evidence that we have gathered to date in support of this approach.

2. A Disciplinary Approach for Supporting Inquiry

2.1 A vision of inquiry for science classrooms

In this design effort, a key step is to articulate a vision of scientific inquiry for students. While there is much interest in involving students in “authentic” scientific reasoning, designing environments for learning requires an articulation of the aspects of scientific practice to establish as goals for students, and consideration of how to integrate those practices within the practices of classrooms. There are several aspects to the argument for involving students in authentic inquiry. The goal is to move classrooms away from “cookbook” or “toy” problems typical of traditional curricula, in which students perform experiments that are given to them. The claim is that instead, students should participate in constructing empirical investigations to address questions they have identified as deserving attention. One strong form of the argument posits that students should work on problems for which a community of researchers is still currently investigating and debating the answers (Means, 1998; Tinker, 1997). While such problems can offer compelling learning contexts and can allow students to contribute data that can be used by practicing scientists, we suggest that there other strategies that can be effective. More important, in our view, is establishing what practices of scientific inquiry and argumentation are the core cognitive and social practices we want students to experience, and what practices are most effective in deeply engaging students in reasoning about scientific phenomena.

The construction of scientific knowledge is a complex enterprise, involving both cognitive and social factors. A cognitive analysis aims to characterize the mechanisms for making sense of scientific phenomena (Clement, 1988; Confrey, 1990; Dunbar, 1995; Tobin & Tippins, 1993), and reasoning about the connection between hypotheses and empirical support (Klahr & Dunbar, 1988; Kuhn, Amsel, & O'Loughlin, 1988). From a social perspective the choice of experimental procedures and hypotheses are a result of communication, debate and negotiation with peers (Cetina, 1995; Hawkins & Pea, 1987). Even when scientists are working alone, their actions are driven by considerations of their community, of the audience for the products of their work (Latour, 1988).

While science is often considered a single, unified enterprise, recent sociological and philosophical studies depict the scientific enterprise as a family of distinct sciences. Scientific disciplines, such as experimental high energy physics or molecular biology, are distinguished on many levels, in their framing of questions and their criteria for knowledge claims (Cetina, 1996; Cetina, 1999). Indeed, even within a scientific domain such as biology, individual disciplines differ in significant ways in their approaches. While molecular biologists primarily build theories through experimentation, research in evolutionary biology typically requires observational arguments and model-testing rather than controlled experiments.

This examination of authentic scientific practice has several implications for science education. First, students should employ a multiplicity of cognitive, social and material tools in order to negotiate primary data and construct explanations for novel phenomena. Second, science classrooms need to include social contexts in which learners present and defend their ideas, and negotiate actions and interpretations as a community. Third, the specific practices that distinguish particular scientific disciplines should be a focus of science learning.

2.2 Theory articulation in problem scenarios

An important aspect of crafting inquiry experiences for students, which is consistent with this characterization of science, is to expose students to a wide variety of scientific endeavors. These design efforts should focus more on maximizing the breadth of conceptual and material approaches, rather than a breadth of content topics, in order to provide students with a fuller perspective of the many facets of scientific inquiry. In the BGuILE project, we directed our design efforts toward supporting a type of investigation that has not received much attention in science education (particularly in the realm of technology-supported inquiry). To articulate this approach, we can characterize investigations according to (1) the investigation method and (2) the relationship between the investigation and theory development.

(1) Observational investigations: Most of the BGuILE investigations employ an observational methodology. The scientific enterprise is most commonly associated with experimentation, in which knowledge claims are based on comparing observed outcomes resulting from the control and manipulation of variables. Indeed, educators often speak of “the” scientific method, referring to the process of hypothesis testing through experiments (DeBoer, 1991). In contrast, observational investigations are used in those investigations within scientific disciplines in which it is not possible to manipulate variables, such as many investigations in astronomy, earth sciences, and ecology and evolutionary biology. In lieu of manipulating variables, comparisons are constructed across time, location, events, objects, and populations. These comparisons can reveal changes, trends and differences. Scientists use these patterns of data to test models and construct arguments based on patterns of converging evidence.

(2) Theory articulation: A common image of science is Newton sitting under a tree, observing an apple fall to the ground, and formulating laws to explain and predict these types of phenomena. However, the discovery and formulation of new laws and theories is not the sole orientation that scientists take toward theories. In many cases, scientific activity involves theory articulation — elaborating a theory, and enriching the corpus of evidence in its support by applying an existing theory to explain novel phenomenological instances (Kuhn, 1970). Much of the research on scientific reasoning assumes rule discovery as the

paradigm of scientific work and neglects this critical type of reasoning (Ohlsson, 1992).

This approach of theory articulation seems particularly well suited for crafting problems in rich observational domains. In some domains, the goal is to develop simple formal laws. For example, in the physics domains of optics and mechanics, students can experiment in order to conjecture and test simple empirical laws. In contrast, in many domains with probabilistic systems, such as evolutionary biology, animal behavior, and ecosystems, learning involves understanding the application of a general theory to the different types of examples that can elaborate a core concept. For example, the theory of natural selection can be simply stated, but much of the science involves understanding how that theory plays out in different ecological settings with different types of organisms (Mayr, 1988). All living organisms have to obtain food and avoid predators in order to pass on genes, but there are many different forms of the solutions to these problems. Thus, the study of natural selection entails learning the important dimensions on which an organism is adapted to its ecosystem, and the common types of adaptation solutions.

Our goals of observational investigations and theory articulation have led us to adopt a problem-based learning approach (Bransford, Sherwood, Hasselbring, Kinzer, & Williams, 1990; Williams, 1992). The strategy is to craft an investigation around a complex interesting problem that requires the student to apply the target scientific theories and skills. For example, in one BGuILE unit, students investigate a crisis in an ecosystem, and need to explain the death and differential survival of organisms in that ecosystem. Students need to apply the theory of natural selection in order to identify the factors constituting a stress on the population, identify the traits of the organism which are variable and important to the organisms' survival, and link the patterns of survival to patterns in these traits.

Thus far, we have articulated a strategy integral to many science disciplines in which students collect observations to test hypotheses. Their goal is to elaborate theories by applying them to make sense of complex, often non-deterministic phenomena in puzzling problems. We next turn to the question of the types of understandings and skills that are involved in using theories to make sense of problems.

2.3 Connecting investigation goals, domain theories, and investigation strategies

Learners need to ground their understanding and practice of inquiry processes in an understanding of the goals and products of inquiry. Students cannot be taught the processes without engaging in reasoning about why these processes are both necessary and effective in testing and arguing for theories.

In our view, the particular inquiry processes students practice are a result of viewing general argumentation goals through the lens of particular scientific disciplines. For example, a general scientific goal, such as articulating causal explanations, leads to a core strategy, such as conducting controlled comparisons in order to isolate causal factors. However, practicing scientists understand more than the general need for articulating hypotheses, conducting systematic comparisons, and supporting claims with evidence. Experts know what types of relationships and arguments prevail in their field, and what type of observations and comparisons can yield relevant data for examining their hypotheses. As a result, science in the different disciplines takes on a somewhat different character. The theoretical frameworks within scientific disciplines suggest the types of causal relations necessary for an argument. This type of knowledge is critical in conducting scientific investigations, and is likely to be an area in which novices lack knowledge and skills.

In our designs, we explore an approach that tries to make the relationship between argumentation goals, domain theories and investigation strategies explicit for students. There are two types of relationships we need to support for students. The first is the connection between the argumentation goals and investigation strategies. In learning and practicing a strategy, students need to see how that strategy affects the type of inquiry product they produce. The second connection is between the general scientific and the discipline-specific levels. We design tools and artifacts that make the discipline-specific strategies and characteristics of the resulting explanations explicit for students. This approach is illustrated in Table 1.

Table 1 shows how we go from general scientific to discipline-specific to the design of the associated tools. In the first row are examples of general scientific goals and the associated strategies. In the second row we see how these goals and strategies are specified within a particular discipline, in this case, natural selection. Opposite the investigation strategies are tools we have built to enable students to perform that strategy. As we will see, the tools are designed to make these strategies observable and explicit in students' interactions with data.

Table 1: A Discipline-Specific Scientific Reasoning Model

(Adapted from Sandoval, 1998)

Knowledge about Inquiry Goals and Products	**Investigation strategies**	**Tools and scaffolding**
General Science Explanations should articulate causal mechanisms that can explain data patterns. Causal relationships should be supported by sufficient and relevant data.	Perform controlled manipulations of variables to isolate the role of factors in causal relations. Focus on collecting data that can be used as evidence.	Students ask to compare across time on environmental factors. Students compare survivors and casualties on physical and behavioral characteristics.
Discipline-specific Explain how environment can select particular traits of an organism. Explain how selected traits provide reproductive advantage.	Look for factors in the environment that can apply selective pressure. Look for trait variations that enable or impede crucial behaviors.	

Consider a specific path through the table. We see that a general goal of scientific argumentation is to articulate a causal mechanism that explains patterns of data. The need to generate causal mechanisms suggests the use of controlled comparisons, because they enable us to isolate and identify causal factors. Within the domain of natural selection, the goal is to describe the causal components that show how an environmental pressure selects for a particular trait in a population. This suggests that the controlled comparisons should be applied to observations of the populations' environment (the source of pressures) across time (to identify changes). We provide students with a tool that lets them specify comparisons by selecting a comparison type (e.g., across time) and variable type (e.g., environmental factors such as temperature or rainfall). In this way, we communicate that (a) comparisons to isolate variables are a key component of data analysis and (b) examining environmental factors across time is desirable and effective in this domain.

Making the connection between domain theories and investigation strategies explicit may be particularly productive for achieving a balance between content and process goals in science classrooms, since students are continually grappling with content topics as they plan and execute their investigations. Providing support for the acquisition of content knowledge as well as the development of inquiry skills extends beyond the design of software scaffolds to the design of classroom discussions, activities and curricular materials in order to shape the full set of mechanisms through which knowledge is constructed in classrooms.

We have discussed how theories, goals, and strategies interrelate, and the implications of these relations for the design of supportive tools. Scientific goals determine the characteristics of the products of inquiry (column 1). The desired characteristics of the inquiry products determine the needed investigation strategies (column 2). Goals and products can be described at the general scientific level (row 1), but must be articulated at the discipline-specific level (row 2) by taking a science-general characteristic and specifying it in terms of the properties of particular theoretical frameworks of the discipline. Tools then can be designed (column 3) to enable the needed investigation strategies, and to make clear to students what these strategies are, and how they tie into the type of products they need to create. As we shall see in Section 4, our key design strategy is to establish and reinforce these connections between strategies and products in the software and classroom activities.

2.4 A classroom-centered design paradigm

Our design goals are to provide tools and curricula that help learners engage more deeply with subject matter. A key strategy is to consider not only the cognitive demands of this type of learning, but to focus on the influence of the social context of the classroom. Designing tools and curricula must tackle not only the needs of individual learners, but also those challenges and opportunities provided by the social context of the classroom. We have called this approach *classroom-centered design* (Loh, Radinsky, Russell, Gomez, Reiser, & Edelson, 1998; Smith & Reiser, 1998). We need to design interventions that can work within and help shift the social context of classrooms in which the software scaffolds will be used.

There are several implications of the classroom-centered design approach. While our goal may be for software tools to dramatically change the type of work students do in classrooms, it is important to design these tools so that they can be integrated within the existing work practices of classrooms. If technology is going to become an integral part of classrooms, its use must also be seamless. Another consideration of classroom environments is that the teacher will have to play a key role cultivating a classroom culture that emphasizes the values that are inherent in inquiry. Therefore, tools should be designed in a way that will allow for teacher-student interactions around the tools, rather than self-contained activities. In addition, the use of these software environments should be woven within a web of discussions and activities using both traditional and computational media.

3. BGuILE Technology-infused Science Curricula

In this section, we present a brief overview of *Struggle for Survival*, a BGuILE technology-infused curriculum, to provide a context in which to describe our design principles. The Struggle for Survival is a unit for middle school, in which students learn about ecosystems and natural selection through their investigations of a crisis in a Galapagos island ecosystem. Students investigate the various interacting components of a complex ecosystem in order to find out what is killing many of the animals on this island, and whether there is a pattern that explains how some of the animals have managed to survive the crisis. The problem becomes an opportunity for students to apply and extend their knowledge about species interactions, structure and function relationships, and natural selection.

The Struggle for Survival unit is summarized in Table 2. This six to seven week unit is built around an investigation using the BGuILE software environment *The Galapagos Finches* (Tabak, 1999; Tabak & Reiser, 1997a; Tabak, Sandoval, Smith, Agganis, Baumgartner, & Reiser, 1995; Tabak, Smith, Sandoval, & Reiser, 1996). The unit has four basic phases. The introductory activities of Phase A are staging activities, which introduce background knowledge about island ecosystems and motivate the study of an island in crisis in the Galapagos. The unit begins with activities that introduce the influences of geography and climate on ecosystems in general, and then focuses in on the particularly rich ecosystem of the Galapagos islands. Phase B brings the specifics of the problem to the foreground, and connects what students are learning generally about island ecosystems to the specific problem in the investigation, a Galapagos island in crisis.

The computer investigation, Phase C, is the core of the unit. Students work in teams using The Galapagos Finches software to study a rich dataset from the island habitat Daphne Major in the Galapagos (Grant, 1986). Through this dataset, they can explore relevant environmental characteristics of the island and background information about other species of plants and animals. The core of the dataset tracks the physical and behavioral characteristics of the finch population under threat. Students can read through field notes and can examine quantitative data about morphological features of both populations and individual finches. Students can compare subgrops of the population and can look for changes across time to identify trends and relationships that can help explain the effects of the crisis. (We describe some of the specific software tools students use to access and manage data in Section 4.) In Phase D, the unit concludes with student presentations and a discussion to highlight the important positions and evaluate points of consensus and dissension.

Table 2. The Struggle for Survival Middle School Curriculum

Phase A: General Staging Activities (10 classes)	Staging activities provide background knowledge and motivation for the investigation. Brainstorming activities reveal what students believe and understand about island ecosystems. Activities include a geography game using characteristics of tropical islands as clues, student research on how animals are adapted to the local ecosystem of an island, a background video, and readings on Darwin and the Galapagos.
Phase B: Background for Investigation (5 classes)	Activities focus directly on the Galapagos ecosystem and understanding how to investigate ecosystem data. Activities include a video introduction to the Galapagos and the methods scientists use to study the ecosystem, brainstorming about hypotheses, and a mini paper-based investigation in which students work with a small dataset from the software and make a graph that backs up a claim about the data.
Phase C: Software Investigation (10 classes)	Students investigate data using The Galapagos Finches software environment, documenting their developing explanations as they progress. At the midpoint, student teams pair up and critique each other's explanations.
Phase D: Presenting and Discussing Findings (6 classes)	Student teams prepare their reports. Each team present their findings, and the class analyzes key points of agreement and dissension.

This example demonstrates how we use problem-based learning scenarios to provide opportunities for theory articulation. While students need some basic understanding of the theory of natural selection to make progress in the investigation, they need to extend their understanding to make sense of the problem. For example, students acquire a simple understanding of environmental stress and survival value, but the problem context allows the students to consider different environmental factors as candidate stresses, and requires them to work though the implications of an environmental stress for a population.

To date, we have developed four investigation environments now in use in middle and high school classrooms, summarized in Table 3. These environments will be used to illustrate our principles of scaffolding in the next section.

Table 3: BGuILE Interactive Learning Environments

Environment	**Technology-Infused Units**	**Description**
The Galapagos Finches	Struggle for Survival, Evolution (High School)	Students learn about natural selection by investigating how a drought affects the animal and plant populations on a Galapagos island. Students can examine background information about the island, read through field notes, and examine quantitative data about the characteristics of the island's species at various time points to look for changes in the populations.
TB Lab	Evolution (High School)	Students perform simulated experiments on strains of *M. Tuberculosis* to investigate how antibiotics affect bacteria and how bacteria can become resistant to antibiotics. Facilities allow growth and sensitivity experiments, biochemical assays to examine how antibiotics affect the bacteria's metabolism, and sequencing experiments that allow students to look for genetic differences between strains of bacteria.
Animal Landlord	Behavior Matters (middle school), Behavioral Ecology (high school)	Students investigate variation and similarity in examples of animal behavior, studying topics such as predation, competition, and social groups. Students use video analysis tools to extract frames, comparing and annotating them with their observations and interpretations.
The Florida Panther	Conservation biology	Students learn about speciation and the use of scientific research for policy decisions. Students evaluate recovery plans to save the endangered Florida Panther. Students can examine background information about the panthers and their habitat, read through field notes and examine quantitative data about genetic and phenotypic characteristics of the panther population.
Explanation Constructor	Used in conjunction with Galapagos Finches, TB Lab, and Florida Panther	A computer-based journal in which students construct their explanations incrementally while in the midst of an investigation. Students organize explanations around questions and subquestions, and insert evidence from the investigation environment to back up claims.

4. Principles of Support in Curriculum and Technology

Our design represents the union between the general design principles of cognitive apprenticeship (Collins, Brown, & Newman, 1989) and our particular approach to scaffolding inquiry (described in section 2.3) of making the relationship between general inquiry goals, disciplinary theories and investigation strategies explicit. Earlier we argued that the theoretical frameworks of particular scientific disciplines lead to a tailoring of investigation and argumentation strategies. Our designs attempt to help students understand and practice these investigation and argumentation strategies by making them explicit in both the tools students use and the work products or artifacts they create:

- Strategic Tools: We design the tools students use to access, analyze, and manipulate data to make the implicit strategies of the discipline visible to students. For example, when students construct data queries they articulate their query in terms of the key distinctions in the types of comparisons used to build theory in the domain, rather than solely in terms of surface data parameters.
- Strategic Artifacts: We design the work products that students create to represent the important conceptual properties of explanations and models in the discipline. For example, we have students construct hypermedia documents that make explicit the rhetorical structure of their arguments.

In this section, we describe our design principles for supporting student inquiry, and illustrate the principles with examples from curriculum and software. These principles are summarized in Table 4.

Table 4. BGuILE Strategic Design Principles

Structure inquiry around explanatory goals.

- Students generate strategic artifacts representing conceptual and epistemic properties (Section 4.1).

Embed the structure of theories and strategies in the tools students use and the artifacts they create.

- Tools structure students' explanation within discipline-specific theoretical frameworks (Section 4.2.1).
- Tools for access and analysis of data are structured according to explicit, discipline-specific investigation strategies (Section 4.2.2)
- Tools and artifacts explicitly represent the students' epistemological commitments (Section 4.2.3)
- Investigations are focused on producing inquiry products that represent causal explanations and models (Section 4.2.4).

Integrate classroom and technology-supported learning activities.

- Existing learning activities are integrated to introduce skills and concepts needed for the investigation (Section 4.3.1).
- Staging activities enable students to practice requisite strategies in mini-investigations prior to the core investigation (Section 4.3.2).

Support ongoing reflection within the structure of the learning activities.

- Reflective tools are integrated into the environment students use to investigate data (Section 4.4.1).
- Small-group and whole-class discussion activities are integrated within investigations to analyze strategies and build consensus and shared understanding from findings (Section 4.4.2).

4.1 Explanation-driven inquiry

Explaining how and why things occur as they do is one of the central aims of science. The goal of explanation is emphasized throughout BGuILE investigations and is apparent in the design of tools, artifacts, and discussion activities.

We focus on two broad criteria that carry particular epistemological weight: a) explanations should articulate causal mechanisms; and b) explanations should account for observed data. Thus, in our learning activities, students are asked to construct explanations that provide a causal account for why something happens in the way it does. Furthermore, these explanations should articulate how key theoretical principles in the discipline are applied to particular situations or phenomena. For example, while working on the Galapagos Finches investigation in our evolution unit, students must explain in causal terms how natural selection operates on a particular population in a particular environmental context. Thus, it is not enough to determine what factor is the cause of a crisis on an island or to determine that a particular generalization has empirical support. The goal is to go further to construct a causal explanatory account of the empirical findings.

In BGuILE units, the teacher performs the initial framing of inquiry as explanation. Prior to students' first investigation in a unit, the teacher directs a class discussion in which students' ideas are solicited about what counts as a good explanation and what counts as evidence. This discussion is directed toward the two criteria mentioned above. When a particular investigation is introduced, teachers reaffirm these criteria and continually help students to apply them. For instance, in the Galapagos Finches scenario, the driving investigative focus is to explain why some finches survive when others do not. In the TB Lab problem, the focus is to explain how tuberculosis bacteria can develop antibiotic resistance. The lion hunt investigation asks students to explain the factors that combine to cause a hunt to succeed or fail.

Once framed, software scaffolds integrate explanatory and investigative supports to maintain the explanatory focus of students' inquiry. Each investigation environment includes a software component to guide students' construction of an explanatory representation of their understanding of the problem. These scaffolds are described in the following sections. In addition, the explanatory thread is maintained throughout inquiry by interleaving self- and peer-evaluation activities with investigation. These evaluations are focused, using rubrics designed with collaborating teachers, on the adequacy of students' current explanations and their evidentiary support. Thus, students' inquiry goals are focused on general epistemic concerns grounded in specific disciplinary frameworks and their investigations strategies, as described in Table 1. The culminating activity for the investigations consists of some form of public communication and critique of students' explanations, either in the form of group presentations or in the form of constructing a class consensus explanation. This type of culminating task situates the learning within a community, which provides an audience for the work and a context in which students are contributing knowledge to the group (Brown & Campione, 1994; Crawford, et al., 1999; Scardamalia & Bereiter, 1994).

4.2 Explicit representation of theories and strategies

A key aspect of scaffolding is to represent knowledge explicitly that is usually tacit (Collins, et al., 1989), and to do so in a way that helps bridge the way novices think about the problem with more skilled reasoning practices (Merrill, Reiser, Beekelaar, & Hamid, 1992). BGuILE's software tools explicitly represent discipline-specific theories and strategies in ways that guide students' inquiry processes and emphasize general, epistemological goals for their inquiry products. The focus on integrating this discipline-specific level of support complements but differs from the scaffolding strategy of providing tools to support general scientific processes, such as the process support of Symphony (Quintana, Eng, Carra, Wu, & Soloway, 1999) and modeling support tools (Jackson, Stratford, Krajcik, & Soloway, 1994; Stratford, Krajcik, & Soloway, 1998).

The next four sections outline our design approaches for embedding the structure of theories and strategies in the tools students use and the artifacts they create.

4.2.1 Representing theoretical frameworks in tools and artifacts

Scientific theories are generative explanatory frameworks that provide a way to make sense of particular phenomena. One BGuILE software tool, the ExplanationConstructor, represents relevant explanatory frameworks within the structure of the students' computer-based journal (Sandoval, 1998; Sandoval & Reiser, 1997). As students explore the data in one of the BGuILE investigation environments, such as the Galapagos Finches or TB Lab, they incrementally articulate an explanation using ExplanationConstructor. This tool is essentially an outline and word processing system tailored for scientific argumentation. Students articulate their research questions and attach one or more candidate explanations to each question. As they write the text of their explanation, they can refer to the *explanation guides* that represent the key causal components of the explanatory framework. For example, the explanation guide invoked with the Galapagos Finches includes the major causal components of a natural selection explanation. These include the identification of an environmental change that can exert a selective pressure; the individuals affected by that change; the trait variation that provides a survival advantage; and the mechanism of advantage. In addition to indicating the content of a particular explanation within a given framework, guides can focus students' investigative activities on generating data that can further their explanation. Components of the theory, as represented in the explanation guides, suggest specific kinds of data to look for in the problem.

These explanation guides provide prompts for students to join the components of their explanation together, rhetorically and conceptually. These prompts are given in discipline-specific terms, but they function in a more general way to emphasize that there are separate components to explanations that have to hang together in a coherent manner. In this sense, explanation guides are an instantiation of Collins and Ferguson's (1993) notion of *epistemic forms*, particular forms of knowledge representation that afford particular *epistemic games*, reasoning strategies and manipulations of the representation that allow particular forms of knowledge construction. Thus, these explanation guides link the general epistemological criterion for causal coherence to discipline-specific conceptual scaffolds, as in column one of Table 1.

Figure 1 shows an explanation constructed by a student working on the TB lab problem, using biochemical assays to explore how antibiotics disrupt cellular processes in TB bacteria, and investigating how TB have become resistant to those attacks.

Insert Figure 1 Here

The following example demonstrates how the explanation guides can help structure students' analysis of their findings. In this example, the students' attempt to satisfy the explanation guides provokes debate on one of the key ideas in the domain, the nature of traits. In considering whether their finding fits the goal of identifying traits, the group disagrees about whether food choice qualifies as a trait. In the course of this debate, the group brings in key ideas about physical traits and the relation between structure and function. In essence, having to structure their analysis of their findings in terms of the theoretical framework embedded in the tools helps students structure their understanding of the specifics of the case in terms of principles of the domain.

Evan: *(reading prompt)* "Environment causes…"

Janie: No!

Evan: Yeah, "to be selected for…"

Janie: Yeah, but that means like…

Evan: // what food they eat //

Janie: … organism with these trait

Evan: // the trait being the food

Franny: Yeah, that's right.

Janie: No, because like, if my trait is to eat steak, and there's no steak, I'm immediately gonna go to something else.

Evan: If you're only a vegetarian and you only eat… you don't eat meat, you're not gonna eat meat. Well, that depends…//

Janie: Are you insane!?

Franny: OK, OK. Don't think of people. Think of these guys (the finches). If they only eat one type of seed with their beaks and that seed is gone then they can't live anymore.

ExplanationConstructor also represents and emphasizes several general aspects of scientific explanations. The ExplanationConstructor representation makes salient the rhetorical structure of arguments. The structure of the journal asks students to articulate questions, and to associate explanations with questions. It is clear from the interface that multiple explanations can be associated with a single question, reminding students that they should be pursuing competing hypotheses.

Finally, and perhaps most important, is that ExplanationConstructor makes the evidentiary basis for the argument explicit. The hallmark of scientific arguments is that claims have to be defended with evidence. Clarity of argument is essential so that the community can evaluate the evidence presented in support of an argument. As can be seen in Figure 1, students embed references to supporting evidence directly within the prose of their argument. Students paste in evidence directly from the investigation environment, and can link it to assertions in their explanation.

In making the argumentative structure an explicit part of the tools students use, ExplanationConstructor is similar to other software tools for hypermedia argumentation, such as CSILE (Scardamalia & Bereiter, 1994) the Collaboratory Notebook (Edelson, Pea, & Gomez, 1996), and SenseMaker (Bell & Linn, in press). It differs in the incorporation of discipline-specific structures to guide the argumentation, and in the tight coupling of the explanation environment with the associated investigation environments.

This conceptual and strategic organization of ExplanationConstructor is an example both of strategic tools and strategic artifacts. The functionality of the tool is designed to encourage students to consider the appropriate discipline-specific components of an explanation, to tie claims to evidence, and to organize their explanations around explicit questions. In addition, the explanation product that results is a strategic artifact that represents the rhetorical structure of scientific argumentation in the particular discipline. Students can clearly evaluate their product in terms of both its conceptual and epistemic adequacy.

4.2.2 Representing investigation strategies

As with the explanation support, our supports for investigation strategies embody general scientific goals within discipline-specific frameworks. This support in the strategic tools for accessing and displaying data helps focus students' reasoning on the core strategies of the discipline, and on aspects of the phenomena that students often find problematic.

The first type of advantage is in making important strategies apparent in the tools. In understanding natural selection in the wild, it is important to examine the survival value of traits that vary within a population. Investigating natural selection entails examining variation in physical and behavioral traits, and looking for patterns of survival that are influenced by those trait differences. Consideration of a trait requires demonstrating a link between structure and its function, to argue for the survival value of the trait. This framework poses conceptual challenges for students, who tend not to see the importance of individual variation in the process of selection (Bishop & Anderson, 1990; Greene, 1990; Settlage, 1994).

To collect data within this framework of evolutionary explanations, scientists do (a) cross-sectional comparisons, comparing different segments of a population, to understand how they differ, and (b) longitudinal comparisons, to compare a population across time. These two types of comparisons are made explicit to the student in the conceptually-based interface in The Galapagos Finches. In deciding what data to access and display in a graph, students have to articulate the type of comparison that fits their investigation goals and current hypothesis. Figure 2 demonstrates a query constructed in the population query interface and the resulting data display. The first column shows the two types of comparisons, longitudinal, called "seasons," and cross-sectional, called "subgroups." The next part of the query specifies the type of analysis within that general comparison type. Thus, students are guided to think strategically about not only what variable they want to view (selected in the menu entitled "physical traits"), but also must articulate the type of analysis they wish to perform. Their options are: (1) individual differences – examine individual values of population members on a target trait; (2) relationship – plot the relationship between two variables; (3) distribution – display the distribution of values on the trait within the population; and (4) number – display categorical data about the numbers of segments of the population, such as fledgling / adults, male / female. Using this strategic tool moves students' access of data from a focus on which variables and parameters to select to a conversation about what they are trying to accomplish, and what strategy they are using to test an idea against the data. In this way, investigation strategies become connected to discipline-specific knowledge goals (row 2, Table 1).

Insert Figure2 a and b:

4.2.3 Representing epistemological commitments

Our representations of explanatory frameworks and investigative strategies not only guide students' inquiry, but also communicate general, epistemological criteria for both their inquiry methods (i.e., strategies) and their products (i.e., explanations). These and other scaffolds reflect epistemological commitments, or "ways of knowing," that we want students to appropriate through inquiry.

As we have already mentioned, students often hold a view of science that fails to distinguish between theories and the experiments and data that support them (Carey, et al., 1989). This failure to hold theory and evidence as distinct often interferes with students' abilities to reason about data and hypotheses (Kuhn, 1993; Kuhn, et al., 1988). One of our design goals has been to make this distinction salient in both tools and artifacts, to highlight the epistemological distinction between theory and data, and to encourage students to actively evaluate their emergent explanations in terms of available data. In ExplanationConstructor, students actively select data from their investigation environments to link as evidence to causal claims, and these data are represented as distinct from the text of students' explanations. In the Animal Landlord, students study examples of animal behavior to isolate and model the key components of complex animal behavior (Smith & Reiser, 1997; Smith & Reiser, 1998). In a unit on predation, students deconstruct lion hunts into what they see as the important causal events, and for each event, students record their observation of the event and their inference of the importance of that event. Thus, the representations that students construct of their emergent understanding of a problem allow them to maintain a distinction between theory (or interpretation of data) and evidence, saliently depicted as the distinction between "observation" and "interpretation" in the interface (see Figure 3). This explicit distinction facilitates discussions geared at understanding the relationship between the two.

For example, in the following classroom dialogue, the teacher questions a pair of students writing their observations and interpretations on an event in one of the lion video segments. Some simple questions provoke a debate between the two students about whether they can assert that the animal is "being sneaky" from the evidence in the video, or whether that is a speculative interpretation of the evidence. The goal of representing strategies and epistemological commitments in tools and artifacts is to focus students on these distinctions and provoke productive debates of this sort.

> Ms. C.: What is the lion doing? *(points to screen)*
>
> Anna: It's being sneaky.
>
> Ms. C: "Sneaky?" I'm not sure what you mean.
>
> Anna: Sneaky. You know, it sneaks around. It's being clever.
>
> Beth: Yeah, but that seems different from the other things. Shouldn't it be stalking?
>
> Anna: Whatever. It's still being sneaky
>
> Ms. C: How do you measure sneaky?
>
> Anna: What do you mean?
>
> Ms. C: How do you describe it?
>
> Beth: You mean how can you tell it's being sneaky?
>
> Ms. C: Yes.
>
> Anna: It's creeping along in the grass. It's trying not to be seen. It's being sneaky.
>
> Beth: Yeah, but that's stalking. Sneaky is more like an interpretation… Sneaky doesn't say how the lion acts.
>
> Anna: It's acting sneaky!
>
> Beth: But what is it *doing*? It's crouching and going slow in the grass. So it's stalking.

Insert Figure 3 Here

4.2.4 A focus on inquiry products

Earlier design research on scientific inquiry has stressed the importance of having students create concrete products or artifacts that represent their understanding (Blumenfeld, Soloway, Marx, Krajcik, Guzdial, & Palincsar, 1991; Crawford, et al., 1999). Our focus on reflecting the discipline-specific nature of arguments has led us to create strategic artifacts that represent students' knowledge-building contributions. The goal of the inquiry should be a documentation (in text or diagrams) of students' explanation or model. For example, the students' ExplanationConstructor journal represents a clearly structured recounting of the questions, explanations, and backing and disconfirming evidence that they have assembled. The journal artifact represents the students' explanation. In investigations using the Animal Landlord, the goal is an explanatory model of animal behavior, which abstracts from the specifics of the data.

Working with the Animal Landlord, students use video as data to construct models of animal behavior (*e.g.*, the interactions between predators and their prey). They begin by annotating the video clips, labeling important actions in the films that contribute to final outcomes (*e.g.*, capturing prey). This results in a collection of "plot structures" that can be compared to look for behavioral variations and similarities across a number of films. For instance, stalking behaviors may look different when the prey animal being hunted is a zebra rather than a buffalo. A software comparison tool helps students compare actions across their annotated video corpus, allowing them to see differences in actions and the ways that various behaviors unfold.

In a sense, the students are using video to perform a common scientific exercise — moving from raw data (the video clips), assigning structure to the data, making comparisons between the relevant features, and finally creating explanatory models. In this case, the modeling activity involves the creation of decision trees, probabilistic models representing the causal paths leading to outcomes (Figure 4). After using the computer tools to find variations in behaviors, students create these decision trees on poster-sized pieces of paper and display them around the classroom. Classroom discussions occur around the trees as students and teachers pose questions for the groups' proposed models, asking why certain nodes and branches appear, and the nature of the supporting evidence. Teachers may ask why a predator would ignore its prey if that node appears in the tree, helping students think about energy benefits (and costs) to a creature.

The decision trees also serve as predictive models. In some of our classrooms, teachers played additional hunting videos after using Animal Landlord. Because the decision trees were still displayed on the walls, students could use them to predict the behaviors of these new creatures. When they discovered that sharks display different types of behaviors than the lions studied in Animal Landlord, they revised their decision trees to reflect this new information. In this way, the exercise of model revision and prediction continued to be a part of classroom activity.

Insert Figure 4 here.

4.3 Integrating classroom and technology-supported learning activities

Helping students take up the intellectual practices and value system of a discipline is the goal underlying the principles of cognitive apprenticeship (Collins, et al., 1989). Learning the "ways of doing" and the "ways of knowing" in a discipline involves developing knowledge of underlying domain principles and skills for data analysis. Instruction involves gradually building students' expertise in orchestrating this knowledge and these skills while engaging in compelling inquiry. Constructing a technology-infused curriculum requires designing classroom-based activities that prepare students for complex software investigations, and off-computer activities that complement the work within the software, and set the students' interactions with the technology in a broader set of social interactions (Edelson, Gordin, & Pea, 1999; Tabak & Reiser, 1997a). Our designs include two components that address this issue. One component involves integrating and adapting activities from curricula typically used in schools, and the other involves designing constrained investigations that conform to our approach for inquiry support.

4.3.1 Integrating existing learning activities within a project-based unit

The goal of the activities that precede BGuILE investigations are to prepare students' conceptual understanding and skill base needed to plan and manage their investigations. We design this sequence by articulating (a) the disciplinary understanding and skills needed and (b) cognitive obstacles posed by typical student prior conceptions. This leads to a set of content and process targets for our activities. Once these targets are identified we draw on existing, commonly used curricula and construct a sequence of activities leading up to investigation activities. For example, analyses of the study of natural selection point to the primacy of variation and structure-function relationships, as well as to the significance of reasoning about changing distributions in a population (Bishop & Anderson, 1990; Demastes, Good, & Peebles, 1995; Jensen & Finley, 1996). This led us to incorporate two activities, one on variation and one on structure-function relationships, from existing curricula into our technology-infused high school unit on evolution. In one activity, students measure the femur length of all the students in the class and construct a histogram of these measurements in order to appreciate that variation preexists in populations, and to develop proficiency in ways of representing and reasoning about distributions of traits in a population. In the second activity students try to perform everyday functions, such as using scissors and opening a door, without the benefit of their thumb (their thumb is taped and immobilized), in order to appreciate how a physical characteristic can enable particular functions.

We contextualize these activities by foreshadowing the driving question of the investigation and noting the relationship between these activities in class discussions. For example, the introductory discussion of the variation activity notes that the students will need to examine the variation of finches on a Galapagos island in order to investigate the crisis in the upcoming investigation. In follow-up discussions to the structure-function activity, the class considers how differences in a trait in a population could affect the type of behaviors that the individuals in the population could perform.

Drawing on existing curricula is an important part of integrating these new curricula within existing practice. We are building on the infrastructure that already exists for supporting science learning, and upon teachers' experience. Rather than introducing the software investigations as self-contained activities, the ideas are strongly linked to concrete experiences that precede the software investigation.

4.3.2 Staging activities to prepare students for investigations

Although we provide some semblance of the full task by framing the introductory and follow-up activities in terms of the upcoming investigations, this does not provide the same type of experience and opportunity to learn as drawing upon the core concepts and strategies within the context of an investigation. Engaging in investigations is key to learning how to orchestrate this knowledge and these skills. However, trying to coordinate such practices for the first time in the context of an extended investigation of a rich dataset poses many serious challenges. The investigation requires learning complex scientific content, learning to link mathematical expressions to a characterization of phenomena (Lehrer & Romberg, 1996), as well as investigation management skills (Krajcik, Blumenfeld, Marx, Bass, Fredericks, & Soloway, 1998; Loh, Reiser, Radinsky, Edelson, Gomez, & Marshall, in press). In order to address these issues, we include *staging activities* in our unit to incrementally prepare students for the more open-ended nature of an investigation.

Staging activities capture the essential features of conducting an investigation — students have a driving question, and they must negotiate primary data in order to construct an explanation. However, they involve a simpler data set and familiar media, such as paper-based materials, and typically involve more guidance in the materials and from the teacher.

For example, we designed a staging activity as part of the middle school Struggle for Survival unit (described in section 3). In this mini-investigation, students are given individual data records of twelve finches, and asked to study the records and attempt to discern any patterns. At this point in the curriculum, they know they are going to be investigating a crisis on the Galapagos island, and they have seen a video showing how the scientists collect data (banding birds, weighing and measuring them, etc.). They are told that prior to getting the full dataset on the computer, they will have some practice drawing inferences from data.

After studying the raw data, and making a table of the trends they notice, they then construct a graph that “tells the story” that they see in the data. For example, in recent classroom trials, students have noticed trends such as the finding that the weight of the birds seems to be lower in the dry season than the wet season, and that the male birds are slightly larger in wing span and weight than the female birds. Students are not told what kind of graph to make and need to consider how to convey the trend they detect.

This staging activity serves to familiarize students with the data in a more familiar medium (printed tables of data) before they use the computer interface to access the data. Second, it provides students practice in asking questions of data in the context of constructing an explanation, but with a simplified dataset. Rather than a graph providing an answer to a question posed by the teacher, in this activity, students have to interpret the data and construct a graph that shows the pattern they want to communicate. In this way, it introduces the idea that one can focus on different patterns and tell different stories from the same data.

The staging activity we designed for the high school unit on evolution took on a somewhat different form. In this activity, The Marine Iguana, students are presented with a “problematic” natural phenomenon that they are asked to explain, similar to the Galapagos Finches investigation. In this problem, students are asked to explain why subgroups in a population of Galapagos marine iguanas forage at two different sites. Students receive a packet of paper materials that includes the same type of information that is available in the Galapagos Finches investigation, such as graphs showing morphological population data (e.g., snout length), profiles of individual iguanas, and field notes with behavioral descriptions (e.g. descriptions of iguanas foraging). Moreover, the data is structured in the same way as it is structured in the Galapagos Finches, according to our articulation of the intersection of theoretical principles and investigation strategies in this domain.

This activity starts as a teacher-directed activity, and students gain control and direct the activity midway through the investigation. The teacher initially leads the investigation, helping students formulate sub-questions and hypotheses, decide on relevant observations, as well as analyze and interpret the data. The activity continues with students completing the investigation in small groups. This structure provided an opportunity for the teacher to model how to execute particular strategies, as well as voice the rationale for performing these strategies at particular junctures in the investigation. This form of teacher modeling prior to student-directed practice with the strategies is important in helping students learn to direct their own learning (Brown & Campione, 1994; Brown & Palincsar, 1989; Loh, et al., in press; Palincsar & Brown, 1984).

Designing different staging activities around investigations provides a mechanism for tailoring investigation-based units that utilize the same software environments to different audiences. For example, the middle school activity addressed the needs of the middle school students who were less proficient with graphs than the high school students. The Iguana activity catered well to the more stringent requirements for the high school students for achieving content learning goals, by providing additional experience in applying principles that are drawn from the theory of natural selection to explaining an episode in nature.

4.4 Ongoing reflection

A key need in conducting complex investigations is to engage in ongoing reflection as the work proceeds (Collins & Brown, 1988; Loh, et al., in press). Students need to continually re-evaluate their investigation plans, evaluate the status of their hypotheses, synthesize findings so far, reconsider previous understandings, and redirect their investigation as needed. We have two complementary strategies for supporting these reflection processes. First, we provide tools that encourage and structure reflection while students are conducting their investigations within the software environment. Second, we provide support for reflection by interleaving discussion sessions with investigation sessions.

4.4.1 Integrating reflection within software investigations

A key problem in an investigation is managing the information collected, documents created, and generally keeping track of what has been understood and established so far. Students often fail to revisit previous interpretations in light of new and possibly conflicting data (Kuhn, et al., 1992; Schauble, 1990). Creating tools that support the process of reflection has been a focus of our design.

One strategy we have discussed earlier is the integration of artifact creation within the process of investigation. The structure of the ExplanationConstructor is tailored to the particular theoretical frameworks being explored, and it is used in an ongoing fashion as students are conducting their investigation. Students need to consider, as they review the data they have collected so far in a session, what data they should insert into their journal. Teachers stress the incremental elaboration of explanations in students’ journals as they progress through the investigation

We have also incorporated tools specifically designed to help students manage their collected data and their interpretations. In the TB Lab, Galapagos Finches, and Florida Panther environments, all data displays constructed by students are automatically stored in a Data Log (see Figure 5). The Data Log records the time of the data collection, the nature of the comparison (saved as the title), and the data display itself. In addition, any background data that students retrieve can also be saved in the Data Log. A typical investigation results in 30-40 items in the Data Log over a period of one to two weeks. The Data Log allows students to easily retrieve important data they have viewed earlier. In addition, students are encouraged to record their interpretations directly on the record in the Data Log in an annotation field. Students document what important pattern they noticed in the data display, its significance for the investigation, questions that it raised, and so on. These annotations can help students locate particular data they felt was important when they are writing their explanations in the ExplanationConstructor.

Insert Figure 5 Here

Another important tool in the Data Log for managing the collected data is the ability to classify the significance of data with respect to the investigation goals. Again, we structure this process from the discipline-specific theoretical frameworks driving the investigation. The Data Log implemented within the Florida Panthers and Galapagos Finches is tailored with a particular set of categories. For example, the available categories in the Data Log for the Galapagos Finches are: baseline, changes, differential survival, explaining fitness, and variations. Students can classify any data record as belonging in one of these categories, and can later sort the records according to these categories (see Figure 6). In this way, the important components of an argument suggested by the discipline-specific theoretical frameworks drive students access of the data in the query interface, their management of the data in the Data Log, and their synthesis and articulation of their interpretations in the ExplanationConstructor.

Insert Figure 6 Here

4.4.2 Integrating discussion activities within investigations

A second component of the support for reflection is to structure discussion activities that take place throughout the investigation. Mid-investigation critiques provide students with opportunities to assess their progress while they can still revise and extend their work. Post-investigation assessments provide opportunities for students to compare their explanations, and to develop consensus explanations.

The evaluation criteria for critiques are established during the initial framing discussion in which students and teachers develop criteria for evaluating explanations. As discussed earlier, these discussions are directed to focus students on assessing the causal coherence of their own and their peers' explanations, and to take an active stance in evaluating the relevance and sufficiency of evidence for particular causal claims. The goal is that students be able to reason about which explanations might be better than others and why. These framing discussions result in a written rubric that is available for subsequent critiques.

The creation of software-based artifacts can play a key role in classroom-based discussion activities. As we have described, in most investigations students create strategic artifacts that represent their interpretations within the theoretical framework of the discipline, and help make clear the strategies used in the investigation and argument. These artifacts can be used in classroom activities in which students reflect on these artifacts as objects of their cognition (Kuhn, 1993). These discussions may focus on the progress of investigations, comparisons of strategies and results, and so on.

For example, we orchestrate mid-investigation critiques at least once during the course of an investigation. These are supported by specific software scaffolds. We have structured these critique sessions both as evaluative and collaborative exercises. Within ExplanationConstructor, each explanation can be evaluated with a rating and a justification for the rating. These reviews become part of students' work product, and students are encouraged to justify their ratings in terms of the rubric. Using this feature, we have had groups review each other’s work during investigation.

In the predator-prey investigation, reflection is woven into the investigation itself. Students collaborate during the annotation and comparison of video clips, labeling important features and identifying variations between various hunting episodes. The software highlights similarities and differences between the students’ coding of the hunts, but the students must do the real work of interpreting the data and constructing models to explain what they see. During the unit, groups collaborate to consider how and why variations arise and question their representations of the hunting process.

After investigations, we take a number of approaches to facilitate reflection. These include groups’ self-assessment of their final explanations, using the rubric developed earlier, as well as group presentations to the class in which students need to communicate and defend their findings. Also, consensus-building class discussions are used to generate a shared explanation for the problem at hand, and to push students to generalize from the particulars of an investigation to the broader domain theory. For example, in the high school evolution unit, following the second investigation, students are asked to consider whether or not the seemingly very different finch and TB problems are the same “type of problem” and what relation they have to one another.

5. Studies of BGuILE in the Classroom

In this section, we briefly summarize some of the findings from our empirical studies of students and teachers using BGuILE technology-infused curricula in classrooms. Our empirical studies are presented in more detail elsewhere (Sandoval, 1998; Sandoval, in review; Sandoval & Reiser, 1997; Smith & Reiser, 1998; Tabak, 1999; Tabak & Reiser, 1997a; Tabak & Reiser, 1997b).

5.1 Analyses of work products

At a global level, our analyses of the products students produce in their classroom work suggest that they are generally successful at engaging in inquiry in these rich problems. Most groups of students are able to arrive at reasonably well-justified explanations and models and can recount the evidence on which their explanations are based. For example, in the predation unit, students arrive at qualitative decision trees of predation behavior that mirror the quantitative analyses developed by behavioral ecologists. There is a diversity of models across student groups, but the groups typically succeed in being able to justify their model from their analyses of video data in presentations and classroom discussions. In fact, they notice subtle properties of the behavior in their analyses that take them to advanced topics in animal behavior not usually included in high school textbooks (Smith & Reiser, 1998).

In both the middle and high school units on evolution based on The Galapagos Finches, we see students able to articulate explanations in terms of the theory of natural selection (Sandoval, in review; Tabak, 1999). As with the predation unit, there are different explanations developed by different groups of students that all find backing in the data. In one study, the vast majority of student groups articulated explanations that contained all the causal components of a natural selection explanation: identifying the environmental pressure (e.g., a drought); how it affected individuals (e.g., it led to competition for reduced food); identifying a physical trait that differentiated surviving finches from those that died (e.g., larger beaks); and explaining how that trait provided an advantage (e.g., larger beaks allowed finches to crack open the remaining hard-shelled seeds). This stands in contrast to the difficulty most students experience in articulating the importance of variation in natural selection (Bishop & Anderson, 1990).

We have also considered the inferential validity (Kuhn, et al., 1992) of the explanations students produced. That is, are students' causal claims based on valid inferences from data that they have examined? Perhaps not surprisingly, the validity of inferences decreased in the more demanding parts of the explanation (Sandoval, in review). For example, more students were able to correctly cite an empirical trend in the data that identified a trait that differentiated survivors, but fewer were able to articulate a survival advantage that was based on observable data. Students had largely identified the needed components of an explanation and typically filled those parts of the explanation with plausible and relevant claims, but had some difficult navigating the complex dataset to find the best explanations.

Sandoval (in review) has developed a measure to assess the causal coherence of students' explanations independently of their accuracy (i.e., inferential validity). This argument coherence measure is roughly based on analyses of text structure (Trabasso, Secco, & Broek, 1984), and measures whether cause and effect chains are explicitly articulated and connected to the central causal chain of the explanation. In the study just mentioned, students' explanations were largely coherent, even when they included unsupported claims, suggesting that students understood what it means to write a clearly articulated causal explanation.

Overall, the results suggest that the discipline-specific strategic scaffolds are promising. While not all students can construct equally well-grounded explanations, students generally are able to navigate very complex datasets and construct a causally coherent explanation that exemplifies the target discipline theory.

5.2 Studies of conceptual and strategic understanding

Our initial studies of improvements in students' performance are encouraging. For example, the intensive type of engagement in explaining lion hunting behavior in the Animal Landlord predation unit results in better performance on transfer essay questions from pretest to posttest. The essays on the posttest contain more causal arguments and a greater proportion of justified points drawn from the behavioral ecology theoretical framework, rather than from common sense claims (Smith & Reiser, 1997).

Similarly, there is some initial evidence that high school students working with the Galapagos Finches-based evolution unit become better at writing evolutionary explanations, as judged by their performance on pretests and posttests (Sandoval, 1998). Students improve on near transfer problems that ask them to explain a natural selection event using a small dataset. In particular, after the unit students make fewer unwarranted inferences on these problems, suggesting that they learn a generalizable notion of the need for causally coherent explanations (Sandoval, 1998).

5.3 Studies of the investigation process

Perhaps the most revealing analyses are the case studies in which we examine the work of individual student groups and the studies of whole classroom discourse. These studies are where we can see the most direct impact of our tools and curricula. In these case studies, we have recorded students' conversations within their group and with their teacher, and their interactions with the software throughout the investigation. Our analyses focus on their incremental understanding of the problem (as manifested in their conversations and their writing in their data log and journals), their strategic decisions, and the construction of their explanations. When we examine the work of individual student groups, we see the guiding effects of the strategic tools, such as the strategic query interface and the ExplanationConstructor. For example, students' investigations are consistently driven by explanatory goals. Students appear to be looking at data to generate ideas for an explanation to their current question, or they are looking for evidence to support a just-recorded partial explanation, or an explanation guide prompt (Sandoval, 1998). The strategic query interface seems to focus students on the types of comparisons they need for their investigation, and becomes a vehicle for teachers to have strategic conversations with students about what they are trying to achieve and what they will learn from particular queries of the data (Tabak & Reiser, 1997a; Tabak & Reiser, 1997b).

The strategic tools also seem to play a role in the groups' self-monitoring. Our case studies suggest that groups' monitoring of their progress is very focused on their explanatory goals. They evaluate their progress in terms of their current explanation, its completeness, the evidence they have to support it, and their remaining questions (Sandoval, 1998).

In classroom using BGuILE materials, we see moves toward a discourse of science. We see teachers systematically and continually pushing students to defend their ideas and back up their claims with evidence (Smith & Reiser, 1998; Tabak, 1999; Tabak & Reiser, 1997a). Teachers helped students elaborate their reports to be more explicit about cause and effect, and to connect their findings to the theoretical framework of natural selection (Tabak, 1999; Tabak & Reiser, 1997a). For example, consider the following dialogue from an urban high school classroom, taken from the mid-investigation strategy discussion.

> Ms. Patrick: A., how do you know that the young ones died off? … (turning attention to whole class) I want to hear how she came up with that because she didn't give me any evidence to support that.
>
> Amalia: Because we went into graphs. We asked them to show us all the dead birds and the graph was mostly all young.
>
> Ms. Patrick: Ok, so you did look at a graph of all dead ones. Did you look at a comparison of dead ones versus live ones?
>
> Amalia: Yes.
>
> Ms. Patrick: So you know when you looked at the comparison it was the low weight birds that were dead?
>
> Amalia: Yes.
>
> Ms. Patrick: And were you sure they were all fledglings or could they have been low weight adults?
>
> Amalia: No, we checked that.
>
> Ms. Patrick: How did you check that?
>
> Amalia: We looked at the profiles.
>
> (Several minutes later.)
>
> Ms. Patrick: What's doing the selecting?
>
> Kevin: Maybe the owls, since all the small ones are dying maybe the big ones are able to fight off the owls.
>
> Ms. Patrick: Fight the owls? Do you know, and this is truly a question that I don't know the answer to, do you know if the owls and the finches might be in competition for food at all?
>
> Student: Yeah, each other.
>
> Kevin: Oooh (yells back to classmate) Didn't you say the owls were eating the finches! (gets confirmation) The owls ate all the small finches and all the ones that could fight back survived.
>
> Ms. Patrick: Oh, so that's an interesting idea, so you think the bigger ones can survive the attacks by owls. What else might be going on? Why are the finches surviving then?
>
> Lisa: Maybe the finches are adults, and maybe they are more fully developed.
>
> Ms. Patrick: What does fully developed mean, what's your idea Allan?
>
> Allan: Maybe some of them are smarter than the owls.
>
> Ms. Patrick: Maybe some of them are smarter than the owls? Could be, could be. What do you think is the selective pressure here, in other words, what's doing the selecting between those who lived and those who died?
>
> Allan: Yeah, their prey... no, no its the finches if its the ones that is big, no I mean that is little, that can't do nothing, obviously they are going to die.
>
> Kevin: It could be the finches because if, um, you say the rainy season is mostly when they mate and it didn't hardly rain in '77 so they might not have mated.
>
> Allan: ooh, ooh!
>
> Ms. Patrick: You know you guys have got a lot of stuff to juggle here. I forgot about the mating, so they are not mating in the wet season either!

In this example, we see students able to defend their findings and point to specific evidence that warranted their claims. We see the teacher continually challenging students to back up their claims, and sometimes suggesting alternatives for them to rule out. At one point, the teacher asks a question for which she says she not to know the answer. In one case, we see a student turn to another for information rather than the teacher (about owls eating finches). Clearly students are still in the process of connecting their understanding to natural selection (some are confused in attempting to articulate the selection pressure). Yet the picture that emerges is one in which students are taking ownership over what they are producing rather than turning to the teacher as the sole authority in the classroom, and in which the teacher helps to establish a set of norms about claims and evidence that characterize scientific discourse.

5.4 Teaching Practice

Another focus of our efforts is to examine the teaching practice that is effective in creating and sustaining a climate of inquiry. As is clear in the previous example, the role of the teacher is key in structuring science discourse and guiding student investigations. Tabak has characterized two collections of strategies teachers use to support inquiry in their classrooms (Tabak, 1999; Tabak & Reiser, 1997a). First, teachers reinforce software scaffolds, by making the conceptual distinctions represented in the software tools a focus of their interactions with students, pushing students to evaluate their claims in light of data, articulate explanations more fully, and so on. Teachers also augment and go beyond what is supported in the software, prompting students to assess their own progress, helping them evaluate inquiry plans, and establishing norms for discourse that encourage hypothesizing and defending claims with data.

Of course there are many challenges in moving this type of technology-infused curricula from the “early adopters” who worked directly with our research group to a broader audience of teachers who may be less prepared for these pedagogical approaches. In other work, we are exploring the challenges teachers perceive in incorporating inquiry and technology in their teaching, and the ways their practice changes when they experiment with technology-infused curricula (Reiser, Spillane, Steinmuller, Sorsa, Carney, & Kyza, 2000).

6. Conclusions

In this chapter, we have argued that the approach of providing instruction and support at the level of general scientific process needs to be augmented with a focus on designing discipline-specific instruction and supports. We have articulated a set of design principles that implement this level of support in the tools students use to investigate and manage data, and in the artifacts they create.

This attention to explanatory frameworks provides a resolution to the false dichotomy plaguing education reform in both the “math wars” and the science reform debates. Education reformers often point to the proceduralized and decontextualized way that many students learn mathematics and science — without connection to their lives, without deep understanding, and focused on vocabulary and algorithms. They are accused by “traditionalists,” including some leading scientists and mathematicians, of trivializing the disciplines in favor of being enamored of “process.” In our view, to teach scientific process is to teach deep engagement with content. To teach students to do inquiry is to teach them to grapple with data by extensively mapping a theoretical framework to rigorously analyze a dataset. To teach scientific process well means not only to teach the process, but to have students engage with the content much more deeply than teaching the content didactically apart from its use in investigations.

It is important to consider the design tradeoffs inherent in this discipline-specific strategy for support. An important goal in designing computer supports in general, and supports for learners in particular, is generality. Naturally a tool that could be used across a range of domains, such as a spreadsheet, has enormous appeal. Why create separate tools for business, science, and mathematics applications? Indeed, a push toward generality has motivated much tool design in the educational technology field. For example, collaborative tools for argument and knowledge-building can be applied across a wide range of educational applications (Edelson, et al., 1996; Scardamalia & Bereiter, 1994; Suthers, Weiner, Connelly, & Paolucci, 1995). General modeling tools can be used to capture and explore the behavior of a wide range of phenomena (Jackson, et al., 1994; Resnick, 1996; Stratford, et al., 1998). General process supports can be built to support the common practices of scientific disciplines (Quintana, et al., 1999).

In contrast, a focus on discipline-specific supports entails tailoring the scaffolds to particular scientific disciplines, at a cost in generality. However, it also enables a degree of integration of tools and potential utility that complements and goes beyond what the general tools can offer. Students using The Galapagos Finches and ExplanationConstructor use two very complex collections of software tools, and yet manage to move seamlessly between them, exploring data in the investigation environment and periodically returning to the explanation journal to review outstanding questions, insert data, or add to the written explanation. These tools can embody a level of direction in strategic prompts not possible with more general tools. The issue of what will transfer to new science settings is an open question. However, given the situated nature of learning, and the difficulty in demonstrating transfer very removed from the original conceptual domain, it seems overconfident to attempt to solve the transfer problem by teaching skills and providing supports at a very general level.

Just as with the specious process versus content debate, we do not suggest we should propose discipline-specific tools rather than general tools, or vice versa. Instead, we suggest that the field needs to explore the design strategies for crafting each type of support, ways to document what each can achieve, and then compare the design tradeoffs.

Acknowledgements

This research was funded by the James S. McDonnell Foundation, Cognitive Studies for Educational Practice. Additional support for curriculum development and studies of enactment has been provided by the National Science Foundation to the Center for Learning Technologies in Urban Schools (NSF grant #REC-9720383). Opinions expressed are those of the authors and not necessarily those of these foundations.

We are grateful for discussions with our collaborator, James P. Spillane. Richard Leider programmed TB Lab and provided graphics design assistance on The Galapagos Finches. We are also indebted to Susan Margulis and Hans Landel for guidance on the scientific content of our Animal Landlord and Florida Panthers environments, to Renee Judd for content guidance on TB Lab, to Angie Agganis, Pamela Lentine, and Eric Fusilero for assistance with software and curriculum design, and to Tammy Porter Massey for assistance with background research. BGuILE would not be possible without the valuable assistance of the teachers who have helped us develop curriculum and provided input into our technology development, in particular Linda Patton, David Goodspeed, Carlos Rodriguez, and Eva Laczina. To request further information about BGuILE software or curricula, see the BGuILE web site: http://www.ls.sesp.nwu.edu/bguile/

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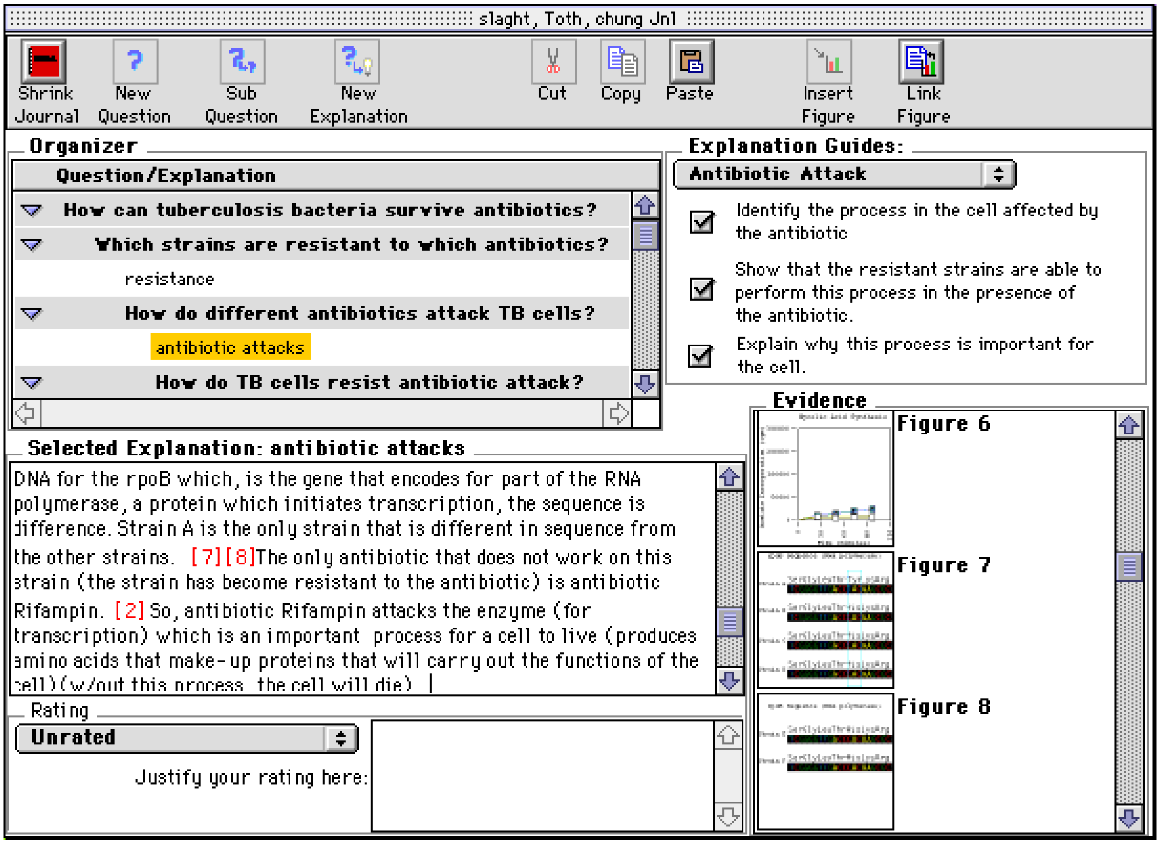


How can tuberculosis bacteria survive antibiotics?

Which strains are resistant to which antibiotics?

resistance

How do different antibiotics attack TB cells?

antibiotic attacks

How do TB cells resist antibiotic attack?

☑ Identify the process in the cell affected by the antibiotic

☑ Show that the resistant strains are able to perform this process in the presence of the antibiotic.

☑ Explain why this process is important for the cell.

Selected Explanation: antibiotic attacks

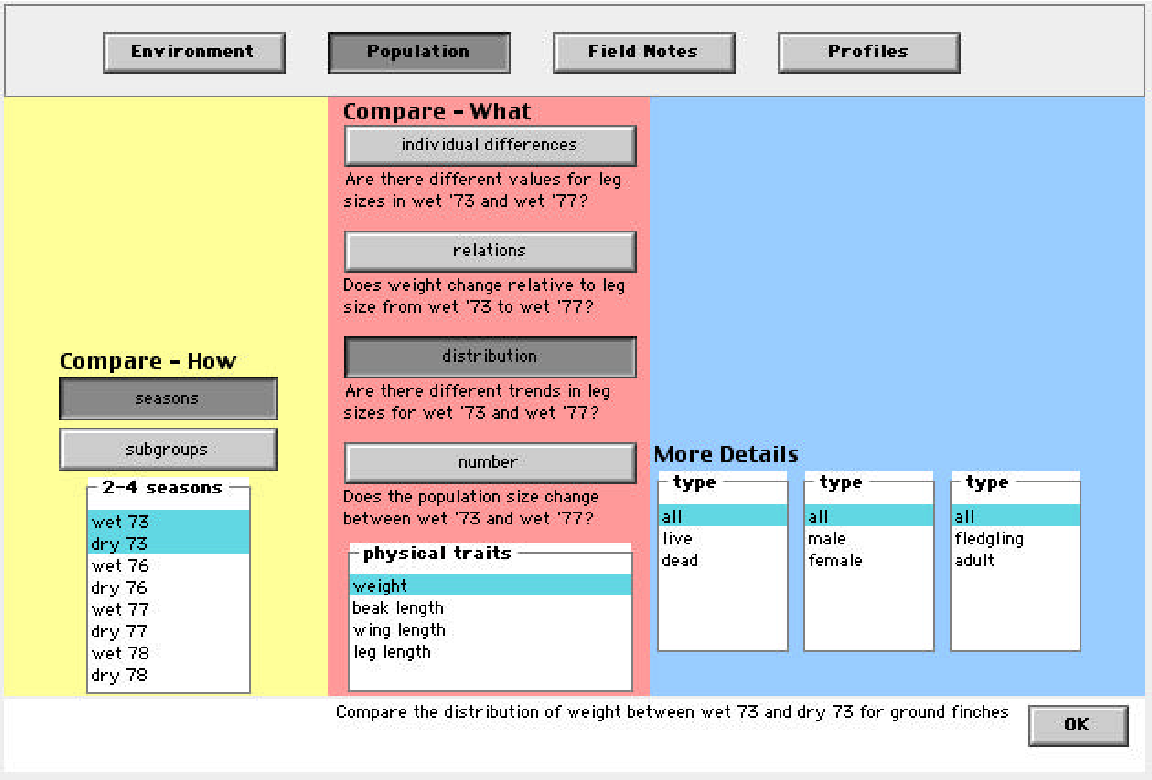
DNA for the rpoB which, is the gene that encodes for part of the RNA polymerase, a protein which initiates transcription, the sequence is difference. Strain A is the only strain that is different in sequence from the other strains. [7][8]The only antibiotic that does not work on this strain (the strain has become resistant to the antibiotic) is antibiotic Rifampin. [2] So, antibiotic Rifampin attacks the enzyme (for transcription) which is an important process for a cell to live (produces amino acids that make-up proteins that will carry out the functions of the cell)(w/out this process the cell will die)

Rating

Unrated

Justify your rating here:

Figure 1. The ExplanationConstructor used to articulate questions, explanations, and the backing support. Shown is a high school student’s explanation for the TB Lab problem. The outline of questions, subquestions, and explanations is shown in the upper left Organizer panel. Explanation guides are shown in the upper right. The selected explanation (antibiotic attacks) is shown in the explanation window, and miniature versions of the embedded evidence are displayed in the lower right panel.



Are there different values for leg sizes in wet '73 and wet '77?

Does weight change relative to leg size from wet '73 to wet '77?

Are there different trends in leg sizes for wet '73 and wet '77?

Does the population size change between wet '73 and wet '77?

Compare the distribution of weight between wet 73 and dry 73 for ground finches

Figure 2. (a) The query screen from The Galapagos Finches. The student has selected a comparison between seasons (first panel), and has selected "distribution" as the comparison type (second panel). Examples of each comparison type are shown beneath each menu item. The particular constructed query is assembled at the bottom of the screen as the students make their menu selections. A seasons comparison distribution graph is shown in (b).

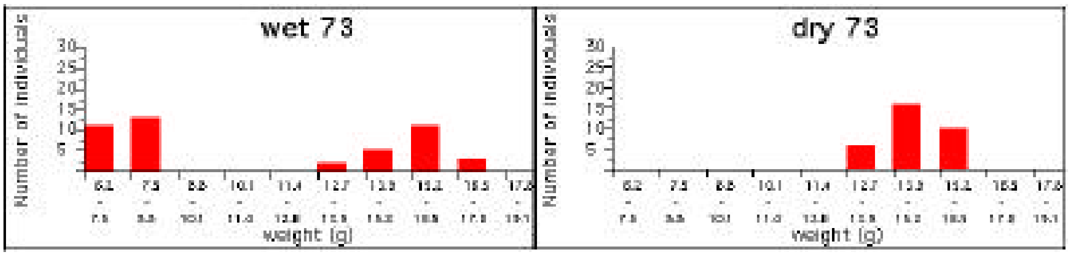
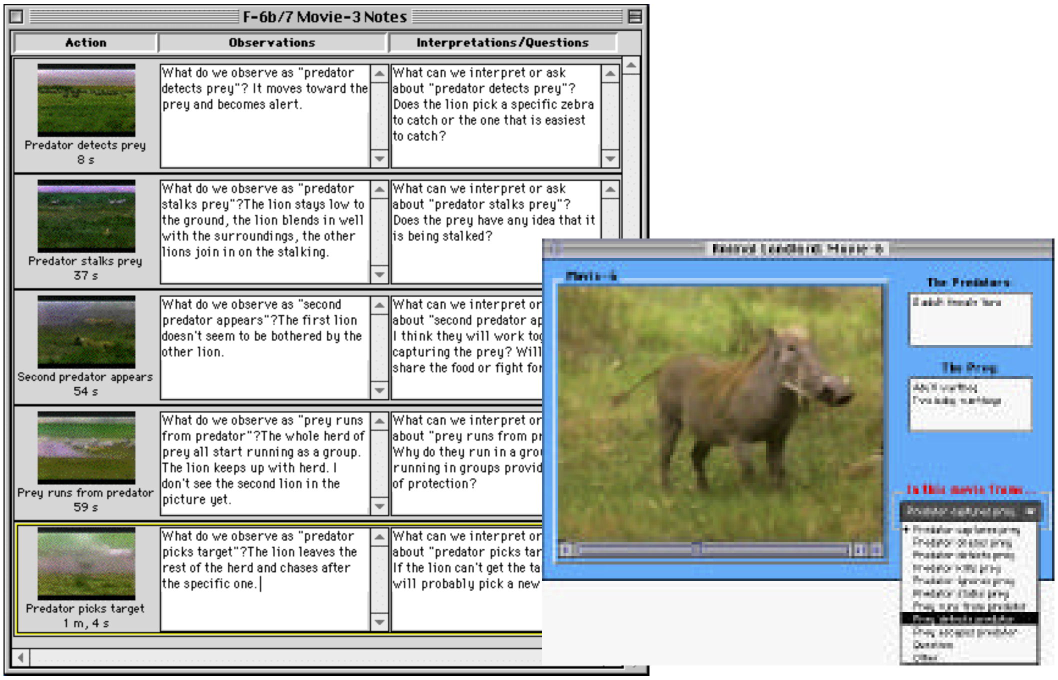


Figure 2 (b). The resulting comparison graph.



F-6b/7 Movie-3 Notes

Action	Observations	Interpretations/Questions
Predator detects prey 8 s	What do we observe as "predator detects prey"? It moves toward the prey and becomes alert.	What can we interpret or ask about "predator detects prey"? Does the lion pick a specific zebra to catch or the one that is easiest to catch?
Predator stalks prey 37 s	What do we observe as "predator stalks prey"?The lion stays low to the ground, the lion blends in well with the surroundings, the other lions join in on the stalking.	What can we interpret or ask about "predator stalks prey"? Does the prey have any idea that it is being stalked?
Second predator appears 54 s	What do we observe as "second predator appears"?The first lion doesn't seem to be bothered by the other lion.	What can we interpret or about "second predator ap I think they will work tog capturing the prey? Will share the food or fight fo
Prey runs from predator 59 s	What do we observe as "prey runs from predator"?The whole herd of prey all start running as a group. The lion keeps up with herd. I don't see the second lion in the picture yet.	What can we interpret or about "prey runs from pr Why do they run in a grou running in groups provid of protection?
Predator picks target 1 m, 4 s	What do we observe as "predator picks target"?The lion leaves the rest of the herd and chases after the specific one.|	What can we interpret or about "predator picks tar If the lion can't get the ta will probably pick a new

Figure 3: Observation and interpretation as explicit objects of the task, and visually distinct in the Animal Landlord interface

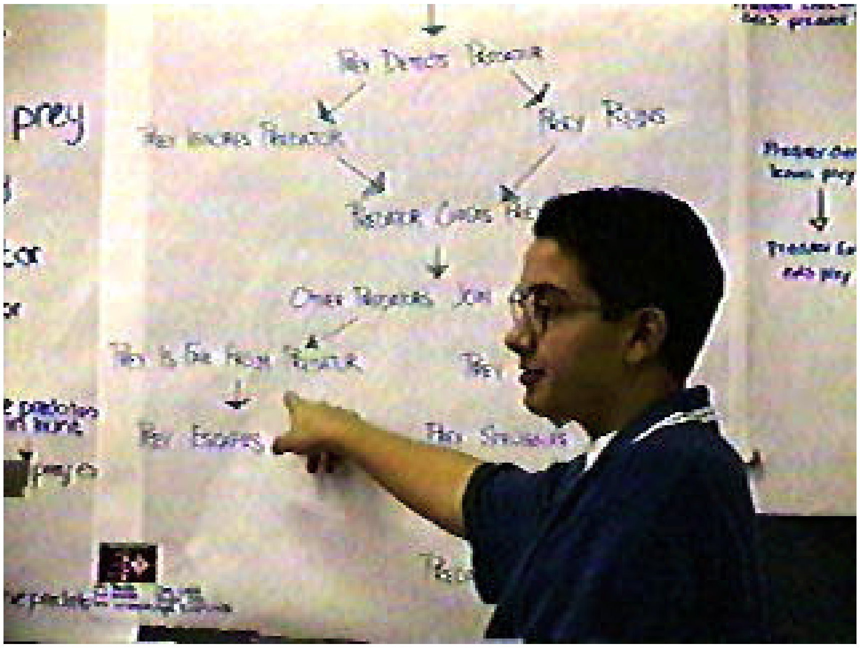
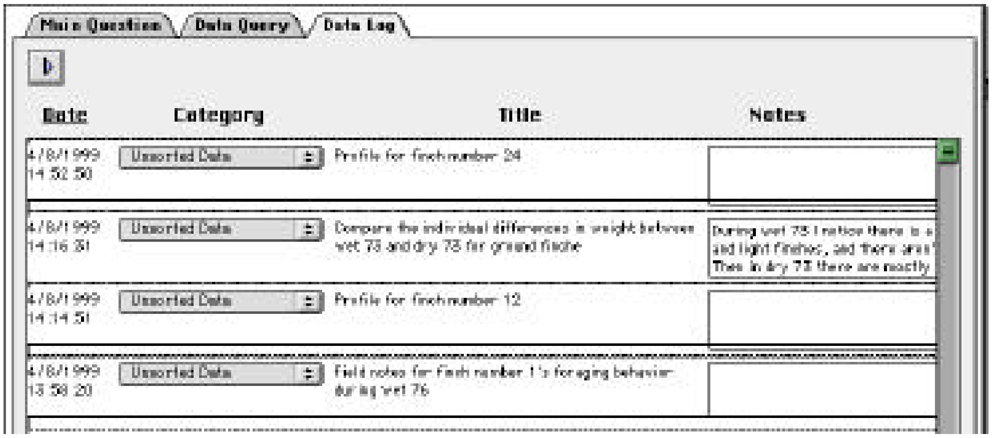


Figure 4.: A student explaining behavioral paths in a decision tree from the behavioral ecology unit.



Date	Category	Title	Notes
4/8/1999 14:52:50	Unsorted Data	Profile for finch number 24	
4/8/1999 14:16:31	Unsorted Data	Compare the individual differences in weight between wet 73 and dry 73 for ground finche	During wet 73 I notice there is a and light finches, and there are Then in dry 73 there are mostly
4/8/1999 14:14:51	Unsorted Data	Profile for finch number 12	
4/8/1999 13:58:20	Unsorted Data	Field notes for Finch number 1's foraging behavior during wet 76	

Figure 5. Collecting data in the data log.

4/12/1999 10:08:50 Profile for finch number 24

Last Observed wet 1973

Figure 6. Managing data through conceptual categories in the Data Log. The group has selected an individual finch data record stored in the data log, and is encoding this data record according to the relevance of the data to their argument.