Justifying imagery: Multimedia support for learning through explanation

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Photographs and video play an important role in classroom learning, serving to illustrate many complex phenomena. However, these images are too often used as "visual aids"—simple explanations of concepts that do not require students to think deeply about the meanings implicit in the imagery. This paper describes an approach to using photographs and video as a primary data source for inquiry learning. We describe a framework for students to collaborate around photographs and video, collaboration that leads to inquiry and the development of explanatory models. We also describe two of our learning environments to illustrate how students can begin to develop predictive theories from image data.

In many North American schools, the dominant educational paradigm is one of "didactic instruction." That is, teachers, textbooks, and other educational media have useful information, and the objective is to transmit this information to students. For many of these students, learning simply means accumulating facts and information. In science classrooms, for instance, many students believe that science is a collection of facts waiting to be discovered, rather than a body of knowledge that is constantly being scrutinized and revised.[1–3] When instructional methods reinforce these beliefs by transmitting facts, algorithms, and other information without showing their relevance to real-world activities, students run the risk of accumulating "inert" knowledge,[4] knowledge that cannot be used in practice and is easily forgotten.

For instance, in most high school science classrooms, students perform hands-on experiments to develop an understanding of what it means to "do science." Yet, the majority of these experiments are still examples of didactic instruction, despite allowing students to learn by "doing." Because students follow a rigid set of "cookbook" procedures developed by teachers or curriculum designers, they rarely have opportunities to develop questions and hypotheses and design experiments to explore scientific phenomena.[5–7] Even though they are doing more than reading textbooks, they are still not engaged in the process of scientific inquiry, and, as a consequence, they may fail to understand how the experiments relate to real science.

Reform movements in education[8–10] advocate a shift from didactic instruction to methods resembling real-world problem solving. The goal is to create learning environments in which students develop their own questions to investigate, design and implement experiments to pursue their questions, and interpret and communicate their results to others.[11] In schools, many domains of knowledge are reduced to knowing discrete pieces of information. In practice, experts in these domains are more concerned with how to perform inquiry and investigation, and how to structure and use information to answer relevant questions.

For many school subjects, students should understand that there are causal structures relating facts

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to one another. For instance, when studying biology, it is not enough to know that cheetahs are the fastest land mammals. It is much more important to understand how they have evolved to run at such great speeds and why other large felines lack the same ability. Similar causality can be found in domains such as history. It is one thing to know that Cambridge, Massachusetts, was once an industrial community; it is much more interesting to understand how and why it evolved into a technological center.

In a sense, the new education reforms are intended to provide students with opportunities to see the causal structure underlying domains of knowledge. One way to achieve this goal is to give students rich contexts where they can conduct inquiry—explore authentic situations, formulate questions from these explorations, develop methods to test their hypotheses, and explain their results to others for critique. Instead of simply being given experiments to see if they can come up with the "right" answers, they should be learning to develop experiments for themselves. Engaging in sustained investigations in rich contexts challenges students to develop strategies for observation and interpretation and to develop causal understandings of a domain.[7,12–15] Instead of focusing on the product of the experiments, we should be training students in the *process* of knowledge construction.

In this paper, we describe a class of activities where students engage in inquiry learning with photographs and video. Visual images provide a great deal of information in traditional instruction, allowing learners to see what might not be evident in textual explanations. Yet the overwhelming majority of images in photographs and video are explained for students; the captions and narratives that accompany the imagery focus our attention on salient issues. In our work, we remove the narratives associated with imagery to create situations where students must discover visual patterns for themselves. We provide them with computational and conceptual tools to help them detect patterns and explain the causal structure underlying these patterns.

We have tried to create multimedia systems where students explore *imagery as data*. Rather than simply presenting information, we have developed environments that challenge students to use information in rich, problem solving contexts. In this paper, we describe two learning environments designed for high school classrooms. The first, *Animal Landlord*, presents digitized nature films to students exploring issues in behavioral ecology. These students annotate and compare film clips to explain how and why predators and their prey behave as they do. The second application, *Image Maps*, presents students with historical images, of their communities, that are used to develop understandings of urban planning and cultural change. In both cases, students collaborate around image data to construct causal models of observable processes (e.g., predation behaviors, community change).

We begin by defining imagery as data, and the use of photographs and video to detect and explain visual patterns. We then describe the framework for annotating, comparing, and explaining imagery as data that have been implemented in Animal Landlord and Image Maps. Finally, we discuss how students have used Animal Landlord and what we have learned from bringing this methodology into classrooms.

Why imagery?

Visual events provide many opportunities for students to pose questions and reflect on behaviors and processes.[16–18] Photographs and videotapes are historical records, and being able to view moments in time can often illustrate points that textual media cannot—watching a lion chase its prey or seeing the styles of dress in the 1940s is dramatically different from simply reading about animal behavior or history. The richness of visual imagery presents possibilities for students to explore interesting issues that are not mentioned in captions and narratives. In a sense, there are opportunities for viewers to engage in problem *posing*; rather than seeking solutions to problems, visual images can serve as starting points for further discussion and investigation.[19] Students can return to the imagery, re-examine their hypotheses, and continue to question and learn. As a result, imagery establishes a context for problem solving, and for generalizing explanations from pictorial evidence.

Imagery as data. However, photographs and video are not typically thought of as artifacts for problem solving and inquiry; they are more likely to be treated as visual aids to accompany text or audio information. For instance, the narratives that accompany documentary films focus attention on salient issues, but the narrator's voice often becomes the principal source of information.[18,20,21] Students may rely on the narratives to explain the "right" interpretations of the video content instead of framing their own questions. Similarly, the use of photographs in classrooms also places an emphasis on explanatory captions to convey information. Photographs are commonly used to illustrate points made in lectures or text materials, but students rarely use them as primary sources for observation and interpretation.[22,23]

In a sense, we can draw distinctions between the use of video as information and video as data. In the former case, video supplements the primary information provided by textual or audio explanations. In many educational films, for instance, narratives provide most of the content, creating self-contained "lectures" complemented with visuals.[21] This information may be useful, but the learning experience can be very different when students use the video as data to discover and explain patterns for themselves. Similar distinctions can be made between the use of photographs as objects and photographs as tools.[23] Again, one is about transmitting information (objects), the other is about discovering information from data (tools).

But there is more to imagery as data than simply removing explanatory information. When domain practitioners use imagery in their work, they understand how to interpret what they see in light of questions and hypotheses that they are investigating. For instance, when behavioral ecologists watch videos of animals, they are looking for potential costs and benefits of behaviors, comparing the behaviors of one animal to others they have seen, and so on. Because they have a set of strategies that help them make sense of the raw video, they are able to create information from the data. In some sense, data become information because experts have tacit, domain knowledge to assist them in making observations and interpretations and developing theories about visual behaviors. High school students rarely have similar opportunities to articulate theories,[24] to develop strategies for interpreting data as information. One of our goals is to help students develop such strategies by placing them in the role of "experts" and teaching them how to observe and interpret image data in light of particular questions that they develop.

So while it is clear that the combination of images and textual explanations can facilitate learning, we are trying to push students beyond accepting these explanations as absolute facts. Instead of providing predetermined problems that have definite answers, we engage students in activities that closely resemble expert practice. That is, we attempt to make expert investigation strategies explicit to students so that they can generate their own questions and hypotheses around photographs and video.

We are not the first to have students explore imagery as data. For instance, there are learning environments where students analyze properties of motion[25–27] and kinesiology[28] with digital video. With these, students measure physical phenomena directly from video clips to develop quantitative stories about distance, rate, and time relationships, or how muscle movements relate to human actions. For instance, "ruler" tools can be applied to video frames to measure the rate that candles burn or the distance traveled during a foot race. Using these quantitative measures, students ultimately fit video evidence to mathematical algorithms describing velocity and acceleration.

The learning experience can be very different when students use video to discover and explain patterns for themselves.

Educational television formats can also present contexts for using imagery as data. Most educational films use narrative to provide a problem and its solution;[20] the narrator presents a problem, and over the course of the film, the solution is unraveled and presented to the viewer. In contrast, programs like *The Adventures of Jasper Woodbury* deliver rich problems, but the solutions are unresolved.[29] In the Jasper adventures, students use clues embedded in the video to reason mathematically about potential solutions. For example, in the "Rescue at Boone's Meadow" episode, the problem is to get an ultralight plane from Cumberland City to Boone's Meadow in the shortest amount of time. Rather than explaining how this can be done, students have to use constraints provided in the video (e.g., the plane can carry five gallons of fuel and 220 pounds of payload) to determine the best plan for a rescue mission. In short, students use these films to discover solutions rather than listening to a narrator give the "right" answers.[20]

Images and video can also be used to demonstrate practices within communities. For instance, Nardi et al.[30] have studied neurosurgeons using video to coordinate their activities in the operating room. During surgery, video of the patient's brain is projected through a stereoscopic microscope. By making the internals of the operation publicly visible, other members of the surgery team can anticipate and plan their activities to ensure efficient team coordination (for instance, the scrub nurse can have the right instruments prepared for the lead surgeon before they are requested). The video is also used by medical students to understand the demands of operating room practices. Again, rather than telling these students how to behave in the operating theater, they must interpret the video for themselves, developing their own ideas about what it means to be part of a surgical team. Describing real-time coordination in text would be difficult, if not impossible, but the video conveys a sense of real practice.

Classrooms are not operating rooms, but they also have many demands and constraints that are difficult to describe with text. Goldman-Segall's Learning Constellations system places students and teachers in the role of "multimedia ethnographers," analyzing and describing videos of themselves in classrooms.[31] By examining their own practices and interactions, participants begin to reflect on what it means to learn in the social context of the classroom. Similar systems have been used to aid teacher professional development,[32–34] providing video clips of "best practices" in classrooms for teachers to reflect upon and adopt in their own teaching.

Investigating and modeling with image data. In all of these applications, learners use imagery as data to conduct authentic inquiry around a problem. We build on this previous work by helping learners create explanatory models and narratives for collections of photographs and video. To do this, they examine imagery seeking answers to a particular question (e.g., "Why are lions 'bad' hunters?", "Why did they eliminate the traffic circle in Harvard Square?"). Rather than simply receiving answers to such questions, students are responsible for observing and interpreting image data and assembling them into models that explain how and why particular events occur. Gradually, they use raw image data to develop hypotheses about behaviors, where evidence for their claims takes the form of significant photographs or video frames. These images are used to construct more complex generalizations of the processes being observed.

Our goal is to change the use of imagery in classrooms by shifting students from recipients of content to producers of multimedia artifacts. Textbooks and traditional school curricula can bias students to think that learning is simply a process of memorizing factual information without argument. Documentary narratives and photographic captions often do the same, presenting carefully crafted stories suggesting a "right" way to view a complex phenomenon. We would like students to understand that experimentation, argumentation, and iterative refinement of ideas lead to the truths found in these image sources. Instead of simply understanding facts, we would like students to understand the reasoning strategies underlying knowledge construction.

We want students to engage in activities similar to the inquiry that expert practitioners go through, using imagery to develop models and theories about phenomena. For instance, behavioral ecologists might use videos of animals to study and analyze behaviors and patterns. Urban planners often use historical images to make decisions about future zoning and construction issues. Students can also engage in this use of imagery as data to develop models and predictions of visual events, and we suspect that much can be learned through these activities.

Students need support to become active observers and investigators of visual data. In particular, if we want them to develop causal explanations and models from visual data, they will need task structures to facilitate the inquiry process. Students can learn by generating questions and hypotheses for themselves, but they also need to understand what makes a *good* question, a *reasonable* hypothesis. Moreover, they need to understand how to analyze photographs and video to create explanatory models. The average student, accustomed to seeing imagery accompanied by narrations and captions, will likely have difficulties in performing critical observation and interpretation of images to develop their own explanatory models. The applications and curricula that we have developed attempt to help students perform inquiry by explicitly modeling expert investigation strategies,[35] articulating strategic knowledge needed to explain complex events and processes with image data.

Strategic activity. Assembling a causal story about complex behavior means organizing observational data into coherent structures or models for explanation. It means thinking about the actions and events involved in the process and understanding their influence on final outcomes. Through consulting with experts in several domains, we developed a task structure for constructing explanatory models from image data. That structure defines four steps necessary for developing causal models that explain behaviors and processes depicted in still and moving images:

1. *Decompose.* Complex processes consist of many constituent, related actions. Interactions between predators and prey, for instance, must progress through stages of detection, stalking, chasing, and finally, capturing. The changes in a city's major modes of transport may progress from horses to trains to automobiles. Identifying these components provides the building blocks for the remaining strategic steps. Because students often fail to understand the importance of intermediate components in a process,[17,36,37] this step guides them to think about behavior as a set of causally connected actions.

2. *Compare.* It is not enough to analyze a single film or photograph of a complex process. Our students investigate libraries of video and images and compare them to look for similar events. By looking for variations in a routine or across time, students can identify patterns that may prove critical to explaining the process. Comparison is important for reducing "confirmation bias," the tendency to look only for evidence to confirm hypotheses rather than trying to refute them.[38] By looking at large data sets of images, students may be more likely to find disconfirming evidence and revise their initial hypotheses.

3. *Identify factors.* Once variations are detected through comparison, students need to perform additional analyses to determine the factors influencing the variance. For example, one might observe that trees are disappearing over time in a collection of urban photographs. To explain why this is the case, it is necessary to look deeper at the images, to identify additional factors that may account for the disappearance (e.g., the number of poles for electric wires is increasing).

4. *Model.* With variations and influencing factors identified, students can generalize causal models that explain the phenomenon under investigation. These may take the form of decision trees explaining the flow of an event or causal chains describing changes over time. Regardless of the form, the modeling step creates an explanatory framework that can be used to predict and design future configurations of the problem space.

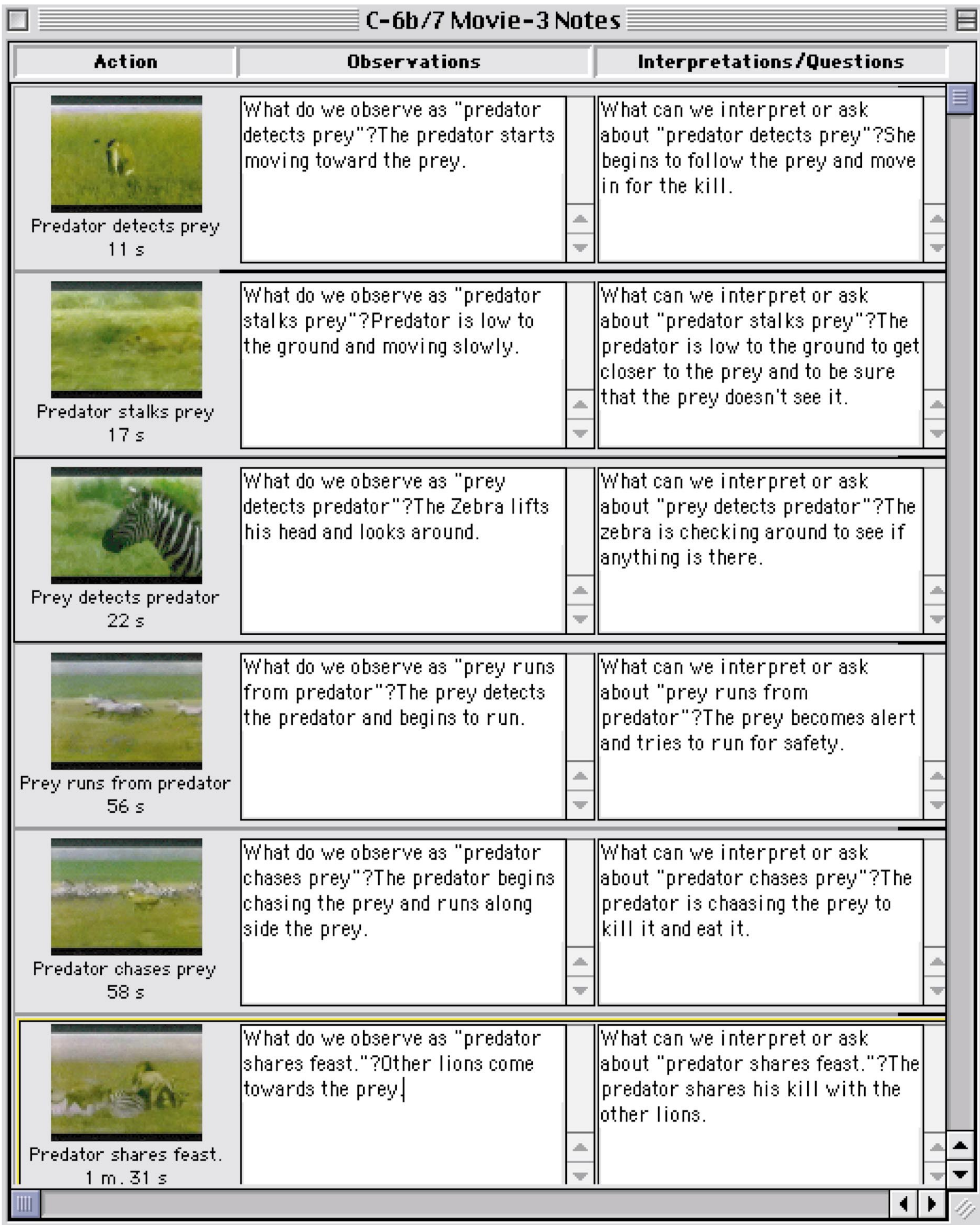
This investigation model provides structure for analyzing complex, observable processes, whether that means field observations or observations of imagery. While students are accustomed to looking at photographs and films, they are not necessarily accustomed to making fine-grained observations and explanations with imagery. The investigation model helps them move from raw image data to predictive theories about observable phenomena. We also provide domain-specific heuristics to help students understand the types of questions to ask during their investigations. For instance, in behavioral ecology, asking about costs and benefits of particular behaviors is a good strategy when trying to explain how and why an action has evolved. In urban planning, one may want to look for variations in land use patterns to understand how neighborhoods arise.

Explaining animal behavior with video

To understand how the investigation model is instantiated in our software and curricular materials, we provide two examples of learning environments that we have developed. The first is concerned with animal behavior. Nature documentary films are commonly used in biology classrooms to introduce concepts in animal behavior, but they tend to provide descriptive overviews of behavior, neglecting many interesting causal processes in favor of straightforward outcomes. For instance, a film might mention that a creature performs a particular behavior without explaining the complexities of how and why it does so. Quite often, the video contains implicit data that can be used to explore causal patterns of behavior.

We developed a video environment, called Animal Landlord, for high school students to investigate the hunting behaviors of the Serengeti lion.[39,40] Only 15 to 30 percent of all hunts attempted by lions result in successful capture,[41,42] and understanding the reasons for this requires investigating the causal interactions between the lion, its prey, and the environment. Students become "field researchers," using digitized nature films to understand how and why lions and their prey interact during the hunt. In conducting their investigations, they explore concepts from behavioral ecology such as social organization, resource competition, variation between individuals and species, and environmental pressures.

Figure 1 Student annotations for a hunting video



The tasks that students perform with Animal Landlord are based on the investigation model described earlier. Groups of three to four students begin by decomposing hunting sequences into smaller behaviors. To do this, they label movie frames with action titles (e.g., "Predator stalks prey," "Prey escapes from predator"). The selected actions for each film are assembled into an annotation window (Figure 1) where additional information is provided. Besides identifying the action, students record the observations that led them to decide that the action is important to the hunt outcome (e.g., "What do we observe as 'predator stalks prey'? It follows at the rear and crouches down low."). They also record interpretations or inferences that can be drawn from the action (e.g., "What can we interpret or ask about 'predator picks target'? The lionesses probably chose the fat one because it would provide the most meat."). The collection of actions, observations, and interpretations form the basis for later discussion and generalization of behavioral models.

Once a number of films are annotated, students load them into a comparison tool to look for similarities and differences across filmed events (Figure 2). By lining up all actions marked "Predator stalks prey," students can visually inspect their annotated films to see how stalking actions differ across multiple hunting episodes (e.g., the type of prey, the amount of ground cover). The interface also allows students to inspect actions before and after a selected event to see how different interactions can lead to or result from similar behaviors. By considering the different paths to outcomes and identifying selective pressures from the video, students can begin to explain behavior in terms of evolutionary theory.

Students create models of the possible predator-prey interactions that can occur during a hunting episode. They currently do this by using their video annotations to create decision trees on posters. These trees represent the space of all hunting decisions made by predator and prey during the observed videos. The decision tree posters are displayed around the classroom, and teachers lead whole-class discussions to help students think about the evolutionary reasons for the paths through the tree (Figure 3). For instance, a teacher might focus on a node marked "Predator ignores prey" to get students to discuss the energy costs related to predation. Such prompting might also lead to discussions of variance between male and female lions, why their energy costs might differ, hence their different hunting behaviors. In other words, the decision trees allow students (and teachers) to question why certain behaviors seem to reoccur during hunting and to examine behavioral transitions in light of optimization and evolutionary adaptation.

The decision trees are also used when viewing nature films after the computer intervention. That is, whenever additional hunting films are shown in class, students use their decision trees to make predictions about the behaviors of the animals and to refine their models if needed. For example, a film on chimpanzees might violate the students' models, because chimps, unlike lions, hunt better when there is less vegetation in the area. This helps students generalize their original models to include creatures like chimpanzees. In this way, we tried to make all classroom nature film exercises incorporate model testing and refinement after the Animal Landlord intervention.

Explaining communities with photographs

Our second example explores urban planning and community change with historical photographs. For most school children, history is commonly presented through textbooks complemented by the occasional photograph, film, or other forms of historical evidence. Like the narratives of a nature film, history texts typically focus on facts, events, and persons rather than the questions, decisions, and heuristics that expert historians use in their work.[43] Being a skilled historian means integrating, completing, and challenging evidence conveyed through multiple knowledge sources,[44,45] but these skills are not typically addressed in high school curricula.

In our second application, Image Maps, students learn to exercise these skills by examining the history of their local communities. When students are taught to explore their outdoor surroundings, they become more aware of the intricacies of man-made environments.[46] Not only can they begin to appreciate architectural patterns, they may begin questioning and posing hypotheses about historical and social aspects of their communities. For instance, the high rent district of Cambridge, Massachusetts, still holds evidence of its industrial past, and observant students may begin to wonder when the area shifted to high technology. A key to answering such a question lies in the historical images of Cambridge. By making these images accessible to students, we hope to develop new ways for them to investigate how and why local communities have evolved over time.

Figure 2 Comparing annotations with Animal Landlord. Each column is a film annotated by students. The window is aligned on the action "Predator stalks prey." The faded columns are films that do not contain this action.

Camera historica. Careful observation of the present can yield interesting questions, but we also need to provide students with a glimpse of a community's past. Archival photographs can provide a starting point for understanding a community's evolution, but these images are not always available in classroom settings. To provide access to archival images, we augmented a digital camera with a Global Positioning System (GPS) and a digital compass (Figure 4). As students explore and photograph their cities, the position and orientation of the camera are recorded along with the image data. By integrating geographic information systems (GISs) with multimedia,[47,48] we can record a "geo-referenced" trail of students' photographs that can be used for inquiry. In this way, students are responsible for collecting field data to produce models from imagery.

Students leave their classrooms to photograph buildings in their neighborhoods. When they return to their classrooms and download their images into the Image Maps software, they can peer into the past. Our application parses each image, extracts the position meta-data, and performs a search[49] of a Cambridge GIS map to return the name of the photographed building. By identifying the current building, we can retrieve and display historical images of the photographed location (Figure 5). In this way, our camera provides a window into the past: students photograph the present and receive historical images of the same location for their investigations of community change.

Once historical images are retrieved and displayed, students can begin annotating and comparing them. Photographs are annotated with features that appear to change over time (Figure 6). For instance, a trail of Cambridge photographs shows the evolution of transportation from horses to railways to automobiles. Students can mark photos with appropriate labels (e.g., "automobiles," "trains") and search on these tags to retrieve similar photos from different eras. The purpose of this activity is to help students notice how similar features may vary across time.

More importantly, students can begin to build models of how and why their local communities have changed over time. The models that they construct are based on the architectural patterns described by Christopher Alexander and his colleagues.[50] A problem or theme is chosen (e.g., "Crosswalks for people"), the context for the problem is described (e.g., pedestrian traffic is conflicting with transportation), and evidence is provided in the form of historical images. In the crosswalk case, students would construct a causal chain illustrating the progression from unmarked pavement to marked crosswalks.

Figure 3 A student presenting a decision tree during a whole-class discussion. These trees are created from the video clips and model all possible actions that predator and prey can take during the hunt.

Figure 4 Image Maps hardware. A Kodak DC260 camera is attached to a Trimble Lassen™-SK8 GPS and Precision Navigation digital compass to provide position and orientation meta-data.

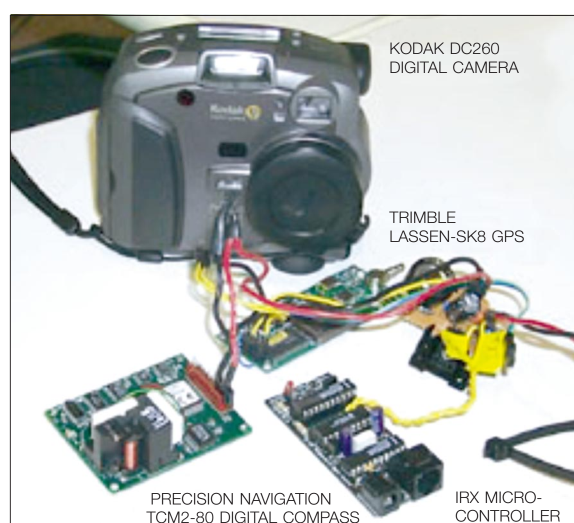
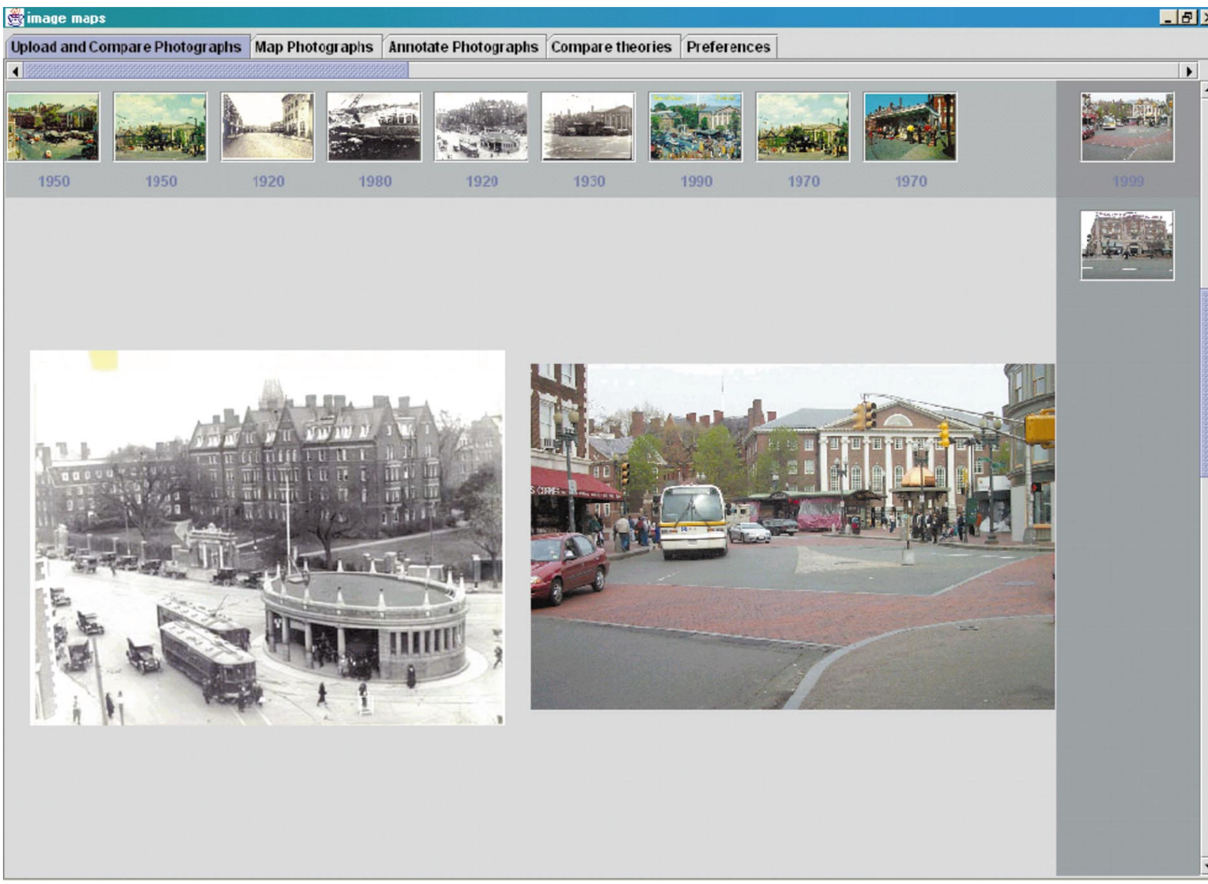


Figure 5 Viewing the past with images of the present. Thumbnails on the right are images taken by students. Choosing one of these results in the display of its larger image and an array of historical thumbnails across the top. The left image is the historical photo chosen from the retrieved collection.



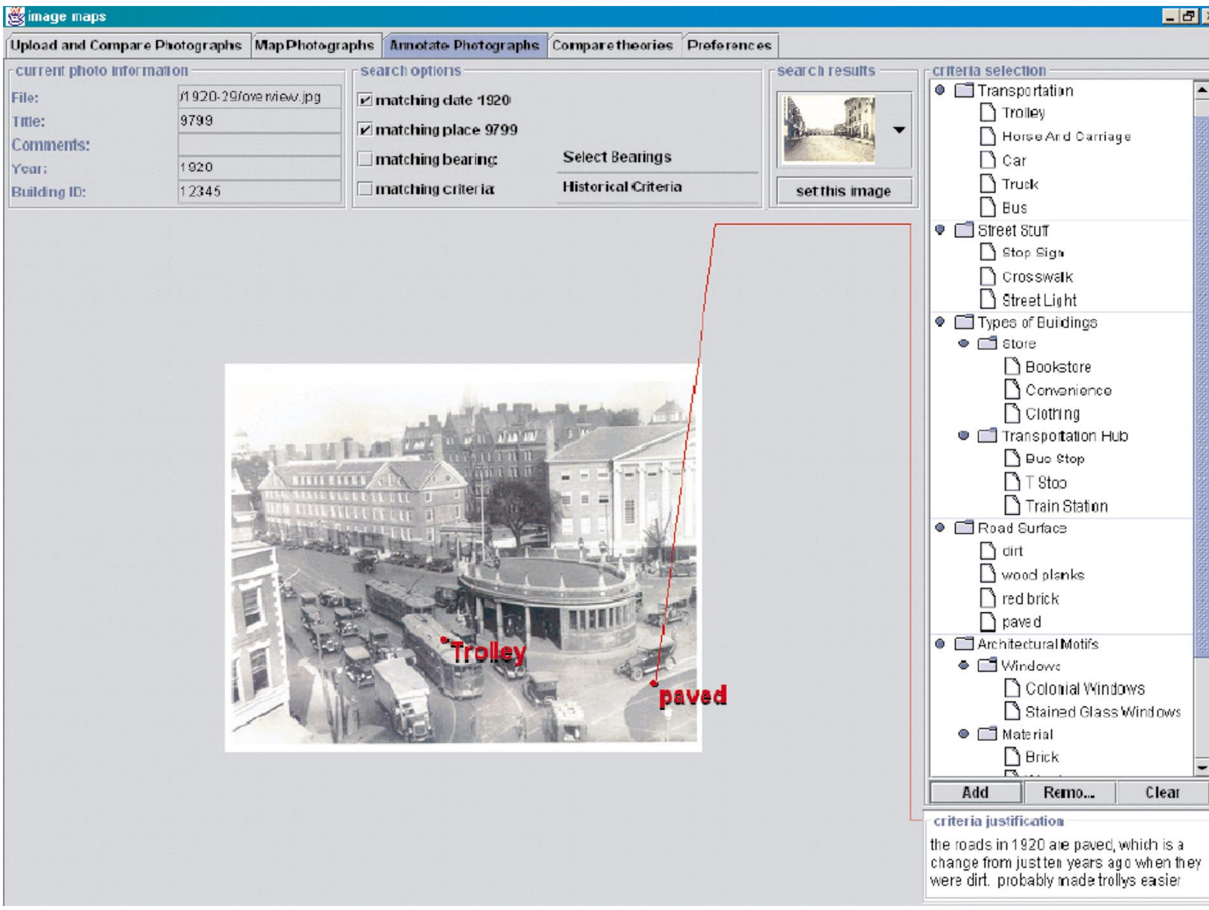
After constructing a number of chains, they can return to the field to see how well their generalizations hold up in unexplored parts of the city. That is, the exercise does not conclude with a single community outing; we expect students to iterate on their hypotheses. For instance, if they think that Harvard Square was rearranged to minimize traffic flow, they may need to return to the location to discover how traffic was rerouted. Additional photographs of the present lead to historical pictures that may help them discover the answer to traffic routing issues.

As with Animal Landlord, students use image data to create models of behavior; in this case, the behaviors are changes in a community over time. As well, students will collaborate and argue around these data to develop hypotheses about change. For instance, we may divide a class into groups in which each group studies a sector of the city. The class as a whole can assemble a more complete model of community change than a single group could on its own. We also imagine that much discussion and debate will revolve around the causal chains that students produce. Teachers will be responsible for helping students make use of investigation strategies as they go into the world to collect their data and to moderate arguments around their hypotheses.

The culture of imagery as data

It is important to emphasize that computer software cannot change classroom learning without additional support. When imagery is used as data rather than information, student attitudes and practices must

Figure 6 Annotating images. Students develop ontologies to characterize interesting features of images. Objects in the photographs are labeled with these features and used to develop explanations of community change.



change from their norms. Teachers must also change their practices, because they can no longer rely on narrative explanations to provide the right answer for a problem. They now have to prepare for student-directed questions that they may not have answers for. In fact, for the domains we have chosen, experts often lack answers for student questions (for instance, no one *really* knows why lions, unlike most felines, live in groups). Thus, for teachers and students, investigating image data can lead to many unknowns.

In this section, we discuss preliminary results from work in Chicago-area high schools with Animal Landlord. In four deployments to classrooms, we revised our original designs to fit into the culture of the classroom. We also worked with teachers to help them understand how to guide student inquiry, helping them to change their expectations about the use of imagery as curricular materials. In a sense, the software tools and video database act as "conversational props,"[51] or digital artifacts that people can refer to during learning conversations. Collaborative inquiry can be mediated by such props,[52] but teachers must also guide students to search through the image data to seek multiple explanations for phenomena being studied.

One goal for our classroom interventions was to foster different attitudes about the use of video in classrooms and to understand what types of learning would occur as a result. Ordinarily, nature films are viewed quietly by students, and they may be quizzed at the end to assess their recall of the content. We

Table 1 Factors varied in the Animal Landlord video corpus

Hunting Factor	Variance in Factor
Amount of visible light	Night, day
Number of lions	1–12
Hunt style	Stalk and chase, ambush
Amount of ground cover	None, low, high
Hunter gender	Male, female
Type of prey	Zebra, wildebeest, buffalo
Number of prey	One, many
Hunt outcome	Success, failure

were trying to create an environment where argument and debate occur during viewing, where students generate their own hypotheses and explanations about filmed events, and where teachers probe and guide student explanations to become increasingly sophisticated. In this section, we discuss some of our findings from a deployment of Animal Landlord, focusing on how classroom practice and the software tools help support the use of imagery as data.

Our observations are based on work with 44 high school freshmen in two Chicago-area biology classrooms, serving mostly upper- to middle-class socioeconomic communities. In this particular school, 54 percent of the students belong to language minorities (i.e., English is not their first language), and the classrooms we worked with reflected this diversity. The majority of the students were 14 years old, and all of them were enrolled in their first high school science course. Classroom sessions were videotaped, and we often interviewed students before and after the interventions to understand how their explanations were changing as a result of working with the Animal Landlord software and curriculum.

Structuring the curriculum. Before we discuss results, we need to point out two crucial features of the research. First, the video clips that students use were carefully selected to promote inquiry and discussion. Second, in order to promote the types of discussions you will see, we had to work with teachers beforehand to help them understand our design rationale and their role in guiding student investigations.

Case selection. We examined many hours of video footage to select the examples that students would use during their investigations. We ultimately selected nine clips ranging from 30 seconds to two minutes as the Animal Landlord corpus. There are about 15–20 variables affecting the outcome of lion predation,[53] and the clips that we selected present examples of each of these variables (see Table 1). The simplest variation is the outcome of the hunt—succeeding or failing to capture prey. More complex variables include the number of predators engaged in the hunt, the amount of ground cover, and the amount of visible light.

The nine clips chosen do not cover all possible configurations of lion hunting, but they seem to be a good approximation for student investigations. By "good," we mean that students can produce models of predator-prey interactions resembling those documented in the ecological literature.[53–56] Each clip varies several parameters at a time, increasing the complexity of student investigations. This variance is important if we want students to develop real problem-solving skills.

Designing with teachers. We also worked closely with teachers to help them understand how they could use the video cases in their classrooms. Five different teachers used the Animal Landlord during our initial iterations. In each of their classrooms, we noticed very different interactions between them and their students that led to different learning outcomes. The teacher's role in guiding inquiry is critical, and, over time, we became better informed about ways to involve them in the design process. Although we developed the software and video materials, we co-developed curricular activities with teachers. This sort of participatory design helps teachers feel ownership over the activities.

In workshops before the iterations, we tried to explain our design rationale for Animal Landlord. We wanted teachers to understand the assumptions and decisions behind the software. For instance, our teachers were not experts on lions or predation, and we had to help them develop intuition about how to guide student inquiry. This generally meant instructing them in the types of misconceptions that students would bring to the problem (e.g., most students imagine lions to be much more successful hunters than they really are). We also had to help them understand the entire process of annotating and comparing video clips to produce explanatory models of behavior. Much of this involved helping them discover the types of domain-specific questions that would push students toward causal explanations.

At the same time, our teachers helped us understand how our work could fit into the culture of their classrooms. Because students are unaccustomed to completely open-ended activities, we had to provide them with some sort of structure. Teachers helped us frame the activities in terms of existing collaboration structures that existed in their classrooms. For instance, teachers developed all of the methods that we used to get students developing and sharing their hypotheses in whole-class discussions. The important thing to note is that we did not simply "drop" the software into classrooms; we worked closely with teachers to coach them through the process of guiding inquiry. More important, as they understood our intentions, they generated their own ideas about ways to best support the activities.

Classroom discussion. Discussions before, during, and after work with Animal Landlord were crucial to the learning experience. As the investigations of behavior progress, teachers talk with students in small-group or whole-class discussions, directing their activities and encouraging argumentation around their findings. These discussions tend to be student-centered; the teacher's primary role is to respond to their queries and to suggest directions for investigation. Students practice their own share of independent discussion as they argue around the films to construct their annotations and decision trees, and these arguments spill over into classroom discussions. Ultimately, learning seems to emerge from student-initiated discussions fueled by the observations made on the computer. This is very different from traditional classroom activities where discussions are initiated by teachers.

Being sneaky. Teachers encourage students to develop causal explanations by constantly prompting them to elaborate their hypotheses. Some of these elaboration prompts are generic—"why," "what else," "tell me more." Others are more domain-specific, drawing on evidence from the video clips and biological theories. A discussion from one of our classrooms where students were arguing that a lion in one of the video clips was "being sneaky" appears below:

1. Teacher: What is the lion doing there [points to video on screen]?
2. Student A: It's being sneaky.
3. Teacher: Sneaky . . . I'm not sure what you mean. What do you mean by sneaky?
4. Student A: Sneaky, you know, it sneaks around, it's being clever.
5. Student B: Yeah, but that seems different than the other things. Shouldn't it be stalking?
6. Student A: Whatever . . . it's still being sneaky.
7. Teacher: How do you measure sneaky?
8. Student A: What do you mean?
9. Teacher: How do you describe it?
10. Student B: You mean how can you tell it's being sneaky? Like what's it doing?
11. Teacher: Yes.
12. Student A: It's creeping along in the grass. It's trying not to be seen. It's being sneaky!
13. Student B: Yeah, but that's stalking. Sneaky is more like an interpretation . . .
14. Student A: Sneaky, stalking . . . it's the same thing.
15. Student B: It's not 'cause sneaky doesn't say how the lion acts.
16. Student A: It's acting sneaky!
17. Student B: But what is it doing? It's crouching and going slow in the grass. So it's stalking.

Lines 1 and 3 show the teacher asking for clarification about the students' work. In Line 7, she gives a specific suggestion to consider how "sneaky" should be measured; in a sense, she is asking them to think more scientifically about stalking behaviors. "Sneaky" suggests that lions act as humans might, intentionally planning to quietly approach their prey. The teacher is pushing the students to describe "sneaky" in terms of measurable attributes. For instance, she later tells them to think about the amount of ground vegetation in the stalking area, because this can hide the lion's approach. Eventually, one of the students begins to understand the point of the teacher's questioning, and she begins to argue with her partner (Lines 12–17).

Being hairy. Another example of classroom discourse occurred when students suggested that female lions hunt more than their male counterparts. This is evident from simply comparing the number of females and males involved in the video corpus, but such a comparison is not enough to explain why this is the case. In this example, the teacher tried to get students to use the video to explain why females might be hunting more than males.

Using the video as evidence, the class claimed that males are significantly larger than females, making them unable to hide themselves in the Serengeti grasslands. Along with their physical size (which can be two to three times that of the female), they have large manes that also increase their chance of being spotted by potential prey. This answer may seem adequate, but the teacher prompted them with a biological strategy, thinking about the costs and benefits of a particular behavior or feature.

18. Teacher: Having a big mane then is a cost to the lion. So there must be a *reason* for it. What's the benefit?

This is a much harder question to answer, and students began developing hypotheses, many based on sexual selection (e.g., "If you have a big mane, you're the king of the pride," or "Bigger manes attract mates."). Such hypotheses could be valid, but the teacher pushed them back to the video to see if there was anything that might suggest why natural selection would favor males to have manes. In this case, the students benefited from the teacher's guidance, for they had difficulties making the leap from hunting behaviors to what appears to be a cosmetic feature.

19. Teacher: How do they kill, lions? You watched the videos.
20. Student 1: Fangs and bites to the upper neck.
21. Teacher: The upper where?
22. Student 1: To the jugular vein . . .
23. Teacher: (interrupting) Found where?
24. Student 1: Huh?
25. Student 2: Where's the jugular found?
26. Student 1: On the neck.
27. Teacher: Oh, so where would that be on the lion?
28. Student 3: Underneath his mane?
29. Class: Oh!
30. Teacher: Oh really . . . so anyone have another theory?
31. Student 4: Oh, so it's like it bites the mane and misses it.
32. Teacher: Yeah, the bigger the mane . . .
33. Class: The harder it is to grab the neck.

In other words, males may have manes to defend themselves from attack. The teacher has students articulate an alternative theory for the presence of the mane; she pushes them to associate a morphological feature—the location of the jugular vein underneath the mane—with an adaptive trait—manes are hard to bite through. More importantly, she prompts students to recall the video data they worked with, encouraging later justification of theories with evidence.

In both examples, student work is driving the content of the discussions. Our teachers tried not to enter the classroom with prepared lectures or topics; rather, they responded to student investigations, choosing particular aspects of their unfolding explanations to critique and further elaborate. In traditional hands-on classroom experiments, students rarely have a chance to investigate questions of their own, develop methods for testing hypotheses, or connect data to conclusions.[5–7] There are also few opportunities for students to engage in theory articulation, applying theoretical knowledge to actual problem solving.[24] The experience of using video as data works because teachers allow and coach students to develop their own observations, interpretations, and questions from nature films. Discussions based on student findings help students to create models from data, hopefully providing them with a stronger understanding of the process of doing and explaining science.

Artifacts as conversational props. The previous discussions suggest that students can engage in scientific discourse around video data when provided with guidance. But without going through the exercise of annotating, comparing, and modeling video as data, it is unlikely that such discussions could have occurred. Students require more than opportunities to "talk science"; they also need opportunities to "do science." We claim that the activities that students perform at their computers before and during these discussions allow them to respond to teacher prompts and to successfully collaborate to produce explanations of behavior. Moreover, it is possible that the software and investigation model influence teacher goals and expectations, shaping the strategies teachers use to encourage student inquiry.

Each strategy in the investigation model discussed earlier is reflected as an artifact in software or on paper (Table 2). For instance, students decompose behaviors with annotation tools designed to help them see that a complex process, like hunting, can be broken into multiple, important actions. Decision trees became useful for illustrating multiple paths to the two outcomes: killing or not killing one's prey. The representations provided by each artifact seem to help students focus on important issues and guide them through the process of using video as data.

Being vigilant. One example of how the artifacts help students during inquiry came when students discovered a behavior known as vigilance. Although it is rarely mentioned in high school biology textbooks or nature films, vigilant or "scanning" behavior—the frequency that a prey animal alternates between feeding and observing its environment to detect potential predators—has been the study of much behavioral ecology research.[54,55,57] Our students detected this behavior while using Animal Landlord's comparison tool. It happens that some films show prey animals cycling between scanning and feeding. In a single film, students may annotate these actions ("Prey looks around," "Prey eats grass") and not notice that there is an interesting pattern. But when multiple films were compared, students noticed these recurring events and began forming generalizations about the behavior.

At least one group in each classroom we observed detected vigilant behavior using the comparison tool. Once it was detected, teachers could prompt students to explain what they were seeing. For example, one teacher asked the students if they could detect variations in scanning patterns across different video clips. That is, does a zebra check its surroundings as often as a buffalo? For that matter, does scan length and time vary when the number of prey animals increases?

Being articulate. A second example of artifacts playing a role in learning concerns the annotation tool. We administered pretests and post-tests to students on the first and final days of their work with Animal Landlord. The tests consisted of open-ended essay questions drawn from university ecology examinations. We were curious to see if student performance would vary as a result of investigating animal behavior with video. While the data are covered more extensively elsewhere,[58] we want to discuss how some of these results can be tied to use of the software artifacts.

The questions that we asked students could never be completely answered with a single response. For example, the question, "What limits the amount of prey consumed by a predator?" raises many potential issues (e.g., the effort required to capture prey, the percentage of unsuccessful captures, and so on). On the pretest, many students gave a single response to the question, such as, "If they're not hungry, they won't eat" and "They know they have to save food for times when prey are scarce." Our first step in analyzing the responses was to note the number of issues raised for each essay question. Table 3 shows typical examples of student responses and the number of points raised in each. An increase in the number of points between the pretests and post-tests indicates that students understand the need to articulate multiple reasons for the execution of a behavior.

Table 2 The relationship between investigation strategies and student-created artifacts in Animal Landlord

Investigation Strategy	Artifact
Observation vs inference	Annotation notes
Behavior decomposition	Annotation notes
Comparison	Comparison tool
Identifying variation	Comparison tool and decision trees
Modeling	Decision trees

Table 3 Sample student responses to pretest and post-test questions and the number of issues coded for each (issues are in italics)

Student Response	Number of Issues
1. If a *predator cannot catch the prey*, then that would limit its food consumption. 2. If a *predator has offspring*, it may have to watch the offspring instead of find food.	2
Its *physical characteristics* such as its teeth, claws. The *speed* that it has. *Ability to see* close and far. *Its diet*. Knowing what looks pleasing and healthy.	4
1. If the *predator is hunting with a group* it may have to save food for the others. 2. If *another predator comes along* the 1st predator may not eat all the prey and will save some for the other predator. Example—cheetah and lions meet. 3. They may not be hungry because *they already ate*. 4. Predator *needs only enough to survive*. Not to eat a lot in case something dangerous comes (another predator).	4

Similarly, each point raised may contain a justification or explanation. Raising an issue such as "a cost of predation is being out in the open" is useful, but it says nothing about why it is important to the creature. Justifying each point raised goes beyond stating what occurred in the video data, moving from descriptive to causal explanations of behavior. Example justifications are shown in Table 4.

Both the number of points and justifications increase from pretest to post-test (Figure 7). The mean number of points raised for each question increased from 2.43 to 3.93, ($F(1, 42) = 28.63$, $p < .001$), and the mean number of justifications for each question also

Figure 7 Mean number of points raised by the students in pretests and post-tests. The shading within each bar shows the number of points with and without a rationale or justification.

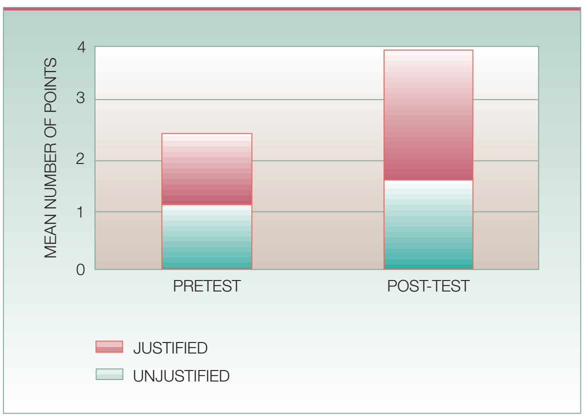


Table 4 Sample responses from the pretest and post-test questions with justifications (in italics)

Student Response
If it is at night. This is important because *at night I think it would be hard to catch prey*.
Takes a lot of energy to make the catch so *by the time it catches it, it is too tired to eat it. So it wastes energy and gets nothing out of it, no energy put back in*.

increased from 1.25 to 2.41, ($F(1, 42) = 14.14$, $p < .001$). These increases suggest that students are refining their initial conceptions of behavior, and how behavior should be explained, to include more knowledge and additional rationale for this knowledge.

What accounts for these increases? We hypothesize that exploring the nature films as data and discussing findings in groups helps students discover and articulate more behavioral issues. More important, we suspect that the annotation exercise plays a large role in these results. The annotation tools provide a structure that reinforces students to (1) be explicit about all actions leading to the success or failure of a hunt, and (2) justify these actions with observations and interpretations. When forced to be explicit about the intermediate actions in the hunt, students gain an understanding of their importance to the overall outcome; this is reflected in the increased number of points. Discussions around the comparison tool may also contribute to our results. With that tool, students argue with each other about issues that were omitted from the annotations and question each other's assumptions about their rationales for including particular events.

We lack data to support the claim that the structure of our curricular artifacts contributes to learning. We know of only one study that examines differences between multiple representations and their impact on collaborative inquiry,[59] but those results suggest that the expressive qualities of a representation can impact the ways that students discuss and make sense of data and evidence. In future deployments of Animal Landlord and Image Maps, we will work with multiple representations for the same task to better understand how they affect investigations of image data.

Conclusion

We have been developing a class of applications that use imagery as a primary source for learning through inquiry. Our students work directly with photographs and video, constructing qualitative models to predict future outcomes and events. Because students often lack an understanding for the importance of modeling,[7,60] we imagine that the immediacy and concrete qualities of imagery may be an appropriate way to scaffold students into additional modeling tasks. Rather than simply looking at photographs or watching videos, we want students to be arguing and debating over differences in image data.

While the software environments give teachers and students tools to begin doing investigations, using imagery as data also means learning to talk about evidence in new ways. Students initiate discussions through questions, observations, and inferences about patterns and behaviors that they discover in the image data sets. Teachers lose some of their control over the classroom agenda, but they compensate for this by guiding discussion, argument, and public criticism of student hypotheses. While we have focused on student learning in this paper, it is also evident that teachers are learning with their students, changing their practices and expectations away from product (do you know *X*?) to process (can you *do X*?).

More than 300 students in 12 Chicago-area classrooms have used Animal Landlord, and a new set of students began using it in 1999 with video content tailored for studies of conservation biology. As with the original version, we hope to see students developing causal justifications of behaviors and their importance for making conservation decisions. The Image Maps project has gone through an initial user trial with MIT and Harvard undergraduate and graduate students. Based on their feedback, we will be redesigning the curriculum and software for a deployment with high school students in the summer of 2000. As we continue to work with students and teachers, we hope to discover more about the types of representations and strategies that can assist inquiry with qualitative image data.

With Animal Landlord and Image Maps, students use imagery as data to construct explanatory models of complex processes—the interactions of predators and their prey and the changes in a community's architecture. The applications also share the same investigation model, the process of annotating, comparing, identifying factors, and creating predictive models to explain the image data. Together, they represent a first step toward reusing existing photographs and video for inquiry learning and model construction.

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