From Misconceptions to Constructed Understanding

The Fourth International Seminar on Misconceptions Research (1997)

Article Title: Domain-Specific Inquiry Support: Permeating Discussions with Scientific Conceptions

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Keywords:
General School Subject:
Specific School Subject:
Students:

Macintosh File Name: Tabak-Biology
Release Date: 10-1-97 A

Editor: Abrams, Robert
Publisher: The Meaningful Learning Research Group
Publisher Location: Santa Cruz, CA
Volume Name: The Proceedings of the Fourth International Misconceptions Seminar - From Misconceptions to Constructed Understanding
Publication Year: 1997
Conference Date: June 13-15, 1997

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Domain-Specific Inquiry Support: Permeating Discussions with Scientific Conceptions

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Introduction

Studies of student conceptions reveal that students often retain misconceptions or do not acquire very deep causal explanations, despite learning terminology and being able to correctly recall facts (Eylon & Linn, 1988). Consequently, educators have argued for an approach to teaching science that focuses directly on uncovering and helping students to build understanding on their prior conceptions, and in making causal explanation an explicit focus in classrooms. Classroom discussions can help students construct scientific conceptions as the teacher elaborates on student articulations of natural processes and extracts essential causal relations from student remarks (Lemke, 1990). These discussions can be particularly productive if students articulate mechanisms they have formulated through their own investigations in computer-based environments, because students can make predictions, test their ideas, and reflect on results by communicating with peers and teachers using a common set of referents (Pea, 1993). Further, if teachers encourage students to recognize and resolve differences they encountered between expectations and actual observations in their investigations then students are more likely to change their understanding (Minstrell & Stimpson, 1996).

We suggest these discussions can be facilitated if the student-directed inquiry takes place in guided investigation environments that are designed to focus students on the key dimensions, relationships and processes in a domain. We call this type of guidance domain-specific strategic support. Interactions with these environments can make discussions more profitable for learning, because the objects of the discourse that are derived from the investigation environment can reflect desired ways of thinking and talking about objects in the domain. We designed such a computer-based investigation environment employing domain-specific strategic support for an evolution unit for high school biology classes. This environment is developed as part of a broader research project, BGuILE (Biology Guided Inquiry Learning Environments), devoted to developing supports for learning biology through student-directed inquiry.

The topic of evolution offers an interesting context for examining the role of guided inquiry learning environments in helping students develop scientific conceptions. Understanding the concept of evolution is key to understanding biology (Dobzhansky, 1973), yet students' persistence in maintaining alternative conceptions is well documented (Bishop & Anderson, 1990; Brumby, 1984; Clough & Wood-Robinson, 1985; Jensen & Finley, 1996; Pedersen & Hallden, 1994; Settlage, 1994). In evolution, as in many scientific domains, it is difficult to observe cause and effect. Learning environments have the potential to make intervening or hidden causes more visible (Collins, 1996). This may be particularly important for understanding natural selection, since people do not have experiential knowledge of such processes (Clough & Wood-Robinson, 1985).

In this paper we describe this investigation environment and a complementary lab activity that simulates natural selection through an idealized model. The two activities foster different aspects of understanding the process of natural selection, and the combination of interacting with the two environments can result in more robust understanding. Our paper outlines the features of the two environments and the facets of understanding they support. This analysis evaluates the types of learning opportunities for conceptual change provided by students' extended investigations in rich computer-based environments, and more directed work with idealized models in lab activities. We examine the use of these activities by teachers and students as part of a larger unit on evolution, evaluating the types of discussions that arise during and following these activities, to explore how the characteristics of the activities provided a productive context for focusing discourse and thinking on the target conceptions.

Components of a Conceptual Change Context

Students enter a learning experience with a vast array of prior knowledge and conceptions about processes in the natural world. This knowledge derives in part from earlier instruction, and in part from students' day to day experiences and observations of the world around them. In some cases, students have sound conceptions that are consistent with current scientific models, and these provide a strong framework for continued learning and understanding. However, it is difficult to observe cause and effect in day to day life, and many processes and forces in the natural world are hidden or invisible, as a result, there are many cases in which students maintain alternative conceptions that are not consistent with the scientific view. In these cases, we want to help students go through a process of conceptual change where they reject their existing, naive conceptions, and accommodate their knowledge and understanding to construct new, scientific conceptions (Eylon & Linn, 1988). Posner et al. (1982) argue that in order for conceptual change to occur students need to become dissatisfied with their current beliefs, and they need to understand how proposed new conceptions can resolve the conflicts they encountered.

Providing students with the opportunity to explain natural phenomena based on interactions with realistic data can create a setting where students may encounter anomalies and inconsistencies with their prior beliefs. This can create important opportunities for conceptual change. However, students may require additional support in order to be able to capitalize on these opportunities. Therefore, designing learning environments for conceptual change requires more than designing activities in which students can investigate and explain particular phenomena. We need to focus students on key principles in the domain to decrease the likelihood that they will pursue irrelevant paths (Lewis, Stern, & Linn, 1993), and to concentrate experiences on challenging alternative and fostering scientific conceptions of the domain. We also have to integrate these experiences with structured discussions that will take place prior to, during and following these activities, to encourage students to explain anomalies, and to challenge their interpretations of evidence. The types of difficulties students encounter in self-directed investigations suggest particular structures and characteristics for both discussion and activity design.

One difficulty students are likely to encounter is that they may raise a hypothesis for the phenomenon that is inconsistent with domain principles, but maintain this hypothesis and explain away anomalous data by interpreting the data in a way that confirms their prior beliefs, even if this interpretation does not take into account all of the available information, or misrepresents the information in some way (Minstrell & Stimpson, 1996). Teachers interacting with students while they conduct their investigations can help students overcome this difficulty. In these teacher-student discussions teachers can tease out and affirm students' sound conceptions and hypotheses to keep students from abandoning a profitable investigation path, but also point to parts of the investigation that may require reworking (Minstrell & Stimpson, 1996).

Teacher-student discussions are also critical for generating new conceptions to replace prior, alternative conceptions. The design of an investigation environment may suggest directions for new conceptions, but students may not have sufficient requisite background knowledge and may not spontaneously reflect on their interactions with the investigation environment, and therefore may not realize the opportunities for new formulations. Teachers can question students about their inquiry process and findings and encourage students to reflect. Further, teachers enter these discussions from the vantage point of holding scientific conceptions of the domain, and therefore can begin the discussion by taking part in students' ways of talking, and then introduce components of scientific conceptions and scientific ways of talking, in order to facilitate the development of scientific conceptions (Roth, 1995).

Another difficulty students may encounter is that they raise a hypothesis for the phenomenon that is consistent with domain principles, but maintain alternative models for interpreting evidence. In this case, students may reject their sound hypothesis rather than question the set of assumptions used for data interpretation. This difficulty relates to Strike's and Posner's (1992) argument that student conceptions are couched within a conceptual ecology – a network of assumptions and beliefs consisting of both specific conceptions about the target phenomenon as well as related conceptions – and that conceptual ecologies influence student conceptions and the direction of their change. Students' understanding of a phenomenon are influenced not only by what they currently believe the process to be, but also by their understanding of related processes, by their criteria for evidence that demonstrates cause and effect, and by their understanding of the goals and nature of scientific knowledge.

In the domain of evolution, students' conceptions and views about living organisms, change over time, and cause effect relationships in the biological world will affect the data that students attend to, and the relationships they draw between pieces of evidence when investigating natural selection. In order to support conceptual change we need to understand the facets of students' conceptual ecologies that create and sustain misconceptions. The environments with which students' interact and the discussions around these interactions need to provide students with opportunities to not only apply and examine their conceptions of the mechanism in question, but to also probe components of their conceptual ecology. Student-teacher discussions should focus on the set of criteria students' use to consider and discount evidence, as well as on their formulation of the process they are investigating.

In summary, components of effective learning environments based on student-directed inquiry geared toward conceptual change include:

- Activities where students investigate phenomena that depict interactions between domain principles in data-rich environments. This provides the opportunity for students to articulate detailed models of domain mechanisms, and challenge any existing alternative conceptions.
- Integrating activities with student-teacher discussions to encourage profitable investigation paths and hypotheses, challenge alternative beliefs, and help generate new, scientific interpretations and conceptions.
- Scaffolding in the learning environment and in teacher-student interactions that focuses students on key domain principles.
- Activities, scaffolding and discussions that consider not only conceptions specific to a mechanism or phenomenon, but broader conceptual ecologies.

We have developed such an environment designed to incorporate these components around conceptions and strategies for reasoning about natural selection. Our design is informed by studies of students' conceptions of evolution that outline key principles of the domain, as well as common points of difficulty or confusion for students learning this domain. These studies suggest topics and principles on which we should center our design. Next, we briefly review research on students' conceptions of evolution, and then describe our learning environment and classroom studies of its use.

Students' Conceptions of Evolution

A large body of research shows that many students maintain alternative conceptions concerning the mechanism of evolution by natural selection, and that these alternative views are resistant to change (Bishop & Anderson, 1990; Brumby, 1984; Clough & Wood-Robinson, 1985; Jensen & Finley, 1996; Pedersen & Hallden, 1994; Settlage, 1994). These studies reveal a set of common alternative conceptions, and present similar assumptions regarding the reasoning that underlies these alternative views. The current scientific model holds that new traits originate due to random mutation and sexual recombination. Therefore, any population consists of individuals that vary in the quality of their traits. These traits survive or disappear due to selection by environmental factors, and become established in a population as the proportion of individuals possessing these traits increases with each subsequent generation (Bishop & Anderson, 1990).

Students' two predominant alternative conceptions concerning the cause of evolutionary change are teleological views, attributing change to need, and Lamarkian views, attributing change to use or disuse of organs and traits (Bishop & Anderson, 1990; Greene, 1990; Pedersen & Hallden, 1994; Settlage, 1994). Many students believe that species change over time as a result of the organisms' need to change due to changes and constraints in the environment. For example, some students will explain that the cheetah evolved to run fast, because it needed to run fast in order to catch its prey. Other students believe that these changes occur, because organisms use or do not use a particular trait, and that the trait gradually improves or disappears in each individual with each succeeding generation. For example, some students describe that cave salamanders evolved from sighted ancestors, but slowly lost the ability to see, because they did not use their sight in the dark caves. Both of the examples of students' alternative explanations differ from the scientific explanation that attributes change to the existence of advantageous traits in the population prior to changing environmental conditions, due to random mutation and sexual recombination.

A number of researchers posit that students appeal to teleological or Lamarkian views, because students fail to recognize variation among individuals in a population, believing that individuals in a population are basically the same, and that any differences in traits are insignificant (Bishop & Anderson, 1990; Pedersen & Hallden, 1994). Given students' assumptions concerning variation, their Teleological and Lamarkian explanations for evolutionary change do have some logical and causal coherence. If all members of a population are alike, yet the predominant characteristics of the population are different between time periods, e.g., cheetah's being able to run 20 miles an hour at time 1 and 60 miles an hour at time 2, then it is reasonable to assume that each of the individuals in the population changed or acquired a new trait. Change in response to need, and change in response to use or disuse of a trait are the ways in which students explain change occurring in each individual in the population.

In order to better understand and characterize the underlying beliefs that may be the roots of students' alternative conceptions, Greene (1990) studied the relationship between students' assumptions concerning key principles of evolution and the types of evolutionary explanations they articulate. He found that having a scientific view of variation is associated with scientific views of additional principles of natural selection. For example, he found that students that recognize that variation exists within a population and that this variation is significant to the process of natural selection also tend to view change as occurring independently of the environment, unlike the naive belief that the environment causes individuals to change. Greene found that a sound understanding of the concept of variation was also related to understanding that evolution involves the increasing proportion of individuals in a population exhibiting a particular, advantageous trait. Bishop and Anderson (1990) regard this understanding as a key factor missing from many students conceptions of evolution.

In addition to identifying students' assumptions regarding component principles of the process of evolution, it is also important to identify related ideas and conceptions – a conceptual ecology. Demastes et al. (1995) studied students' conceptual ecologies for evolution, and how these ecologies affected conceptual change. They found that students' view of the biological world is an important factor in determining the likelihood that students will acquire scientific conceptions. For example, three of four students in their study had a mechanistic approach to science topics, expecting phenomena to be explained through cause-effect relationships; these students made considerable gains in acquiring scientific conceptions of evolution, while the fourth student, who did not have the same propensity for mechanistic thought, made less progress. Similarly, Greene (1990) argues that students' assumptions that natural change is directed, purposeful change are related to students maintaining a view that individuals are essentially alike and variations have little importance.

In summary, studies of students' conceptions of evolution suggest three main categories of alternative conceptions that should be addressed:

- *Variation within a population.* Some students believe that individuals in a population or species are alike, however, the scientific conception is that there are differences in characteristics among individuals in the same species and population.
- *Role of variation within a population*. Although some students recognize that not all individuals in a population are alike, they still do not consider variation as playing a role in the process of natural selection. Existing variation is a necessary condition for the process of natural selection.
- *Evolution as changing proportions of individuals possessing particular traits.* Students often describe the process of evolution as change that occurs within each individual in a population. However, the scientific explanation is that individuals that have an advantageous trait are more likely to survive and have offspring, while individuals that do not have that trait are more likely to die and not reproduce. As a result, subsequent generations have more individuals that have the advantageous trait.

In the next section we describe how we tried to design a unit on evolution that would help students confront their assumptions concerning individuals in a population, and create a context where a more desirable view could emerge. Further, we describe the design of a computer-based learning environment that enables students to confront these views in an inquiry context where their related ideas about causality and change in the biological world surface and interact with their attempts to understand and explain a natural selection event. Our description will focus on this computer-based inquiry environment and a related lab activity, examining the ways in which each can help promote conceptual change.

Complementary Roles of Two Learning Environments

Implementing a conceptual change context

We designed a unit on evolution for high school biology classes that combines lab activities that focus on particular principles of natural selection with investigation activities that depict naturally occurring phenomenon, which inevitably depict interactions among a number of different principles. Activities that focus on specific principles are lab activities that are part of many existing curricula. The activities that depict naturally occurring phenomenon are learning environments where students are asked to investigate and explain a phenomenon by generating and interpreting a rich set of realistic data. The goal of this unit structure is to provide students with two types of experiences. In one, students can confront and challenge their prior conceptions, and construct new understandings by analyzing and synthesizing their observations of a complex phenomenon. In the other, students are introduced to key concepts and processes that provide a source for new conceptions that students can consider when they try to accommodate some of their prior conceptions to account for observations that conflict with these prior conceptions.

Our unit currently includes four lab and three investigation activities in the following sequence: a lab on measuring variation in the class's population (e.g., measuring femur length); a lab examining the functionality afforded by an opposable thumb; an investigation explaining divergence of foraging sites in a population of marine iguanas; a lab that simulates the process of natural selection; an investigation explaining differential survival of a population of finches; a lab examining differential growth of bacteria in the presence of antibiotics; and an investigation explaining how some strains of TB are resistant to some antibiotics.

Students conduct their investigations in computer-based guided inquiry learning environments. These environments include a set of supports to help students organize and manage the complexity of the data available in these rich environments. Some of the supports help students design systematic and informative comparisons. Our inquiry supports incorporate domain-specific strategic support. In a domain-specific strategic support design core domain principles and relationships are translated into ways of interacting with the environment. For example, variation of traits is a central causal agent in evolution. One way to query morphological, structural, information in our environment is by making the selection "what is the variation of structural traits in the population." This introduces variation as a relevant concept and inquiry target.

Discussions are integrated throughout the unit, and play a central role in fostering conceptual change. Students engage in student-student discussions as they work through the different activities in small groups, articulating their interpretations of the data, and reconciling differences among group members' interpretations. The teacher circulates through the classroom engaging groups in discussion as they work through their labs and investigations. In these teacher-student interactions the teacher can prompt students to describe their current theories and understandings, encourage them to reflect on anomalies and inconsistencies they encounter, and suggest new interpretations or investigation paths if they reach an impasse. Finally, whole class discussions are interleaved within investigation sessions (investigation activities extend over a number of class periods). In these whole class discussions the teacher encourages all students to reflect on their learning and to help students generalize from their interactions of the particular case they are investigating to domain principles, drawing on the combined experiences and insights of all of the groups in the class.

These discussions can be particularly profitable if key domain principles, and concepts associated with naive conceptions are the objects of discussion. We propose that having students conduct their investigations in environments that incorporate domain-specific strategic support may increase the likelihood that discussions will focus on these concepts. In the next few sections we discuss the relative contributions of activities for creating conditions that can foster conceptual change: providing opportunities for students to challenge their alternative conceptions, reflect on the sensibility and fit of new conceptions, and focus discussions on concepts that are pertinent to constructing scientific conceptions. We limit our discussion to two of the unit's activities, the Natural Selection Simulation and the Finch Scenario.

Natural Selection Simulation: highlighting mechanisms with idealized models

The goal of this activity is to simulate, using simple objects such as beads, the mechanism of natural selection. In this activity students simulate color change in a population by using a piece of colored cloth to represent a population's habitat, colored beads to represent variation in color in the population and students represent the selective pressure by acting as predators and collecting (hunting) the beads. This activity also introduces students to thinking about the outcomes of natural selection as changing distributions of a trait in the population. Further it suggests methods and strategies for comparing distributions, because students draw bar graphs showing the color distribution in the population before and after a series of “hunts."

This activity addresses the following components of a conceptual ecology of evolution:

Variation within a population

The use of colored beads serves as a striking visual cue for individual differences among the population of "organisms."

Role of variation in natural selection

Most students are familiar and understand the concept of camouflage, and this concept is clearly depicted in the setup of the colored beads against the colored cloth. Many students easily predict that the beads that have the same colors as the cloth will be the ones that will be more readily "hunted," and these predictions are easily confirmed in the activity. Students can see that color affected survival.

Evolution as changing proportions of individuals possessing particular traits

Comparing the number of beads of the "surviving" color at the beginning of the simulation and at the end of the simulation illustrates the change in the number of beads of that color. However, the issue of changing proportions is clearer and more explicit if students chart and graph the number of beads of each color at the start and end of the simulation.

Finch Scenario: guiding inquiry with domain specific support

The goal of this activity is to help students understand the process of natural selection by investigating and explaining an episode of natural selection in the wild. In this problem students are asked to explain why so many finches in a population of finches on a Galapagos island are dying, and more importantly, what enables the surviving finches to survive. This scenario is based on a longitudinal study of finches in the Galapagos (Grant, 1986). This is a computer-based guided inquiry activity where students can access data that includes: morphological information for the population, such as leg length and beak length; individual profiles showing all the tests and measurements available for an individual finch; and field notes with behavioral information, such as descriptions of foraging and mating behaviors.

The investigation environment is designed to incorporate domain-specific strategic support, making explicit and continually reinforcing strategies for reasoning about biological data. Students request data from the system in terms of important conceptual relations such as the distribution of traits within a population, comparisons between groups, and comparisons across time. Data requests are made through a question-based interface, where students select a question type and a question stem to construct a complete question. Question types represent comparison categories and question stems represent dimension categories, an example completed question is "Are there changes between time periods in the variation of structural traits?" (see Figure 1). The software thus directly scaffolds investigative strategies required to explain evolutionary phenomena, such as recognizing variations, changes over time, and relating behavioral and structural information. Students can make comparisons of aggregate data, such as differences in the beak length of live and dead birds in the dry season of 1977, and directly access profiles for individual birds through the graph. Profiles are cross-referenced to field notes to support students' in connecting structural and behavioral data (see Figure 2).

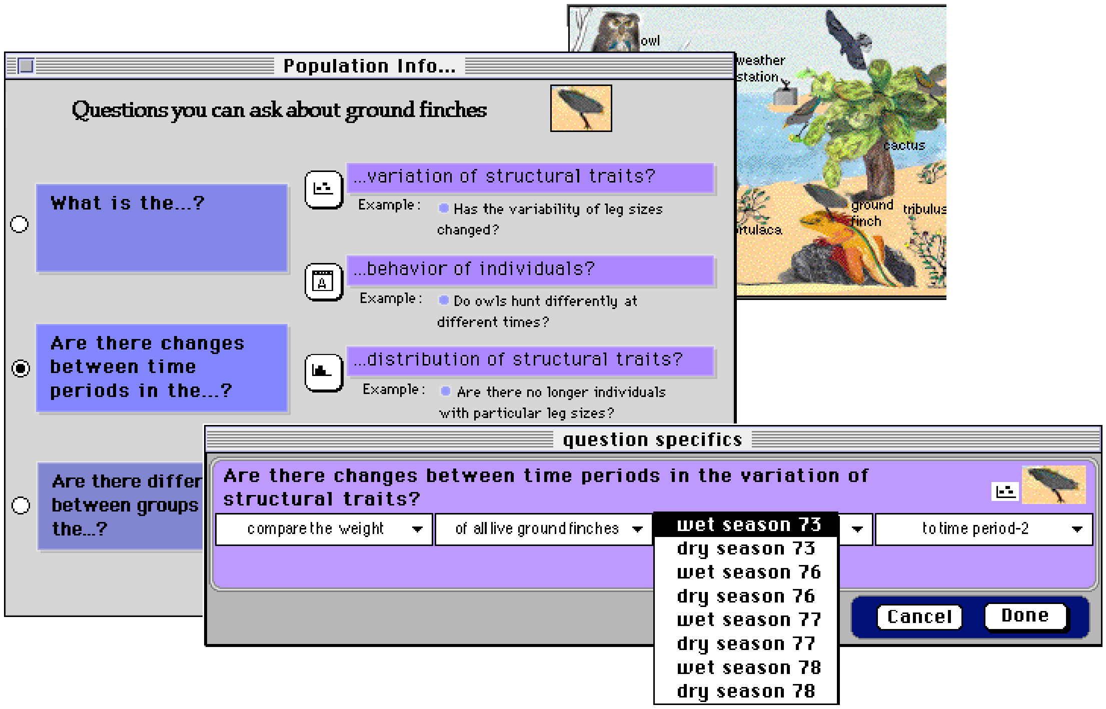

Figure 1: The questions interface and dialogue resulting from selecting "Are there changes between time periods in the..." - "...variation of structural traits?" In the dialogue students specify structure, group, and two time periods.

Figure 2: Graph resulting from the selection "compare weight of all live ground finches between dry season '76 and dry season '77." Clicking an individual data point in the graph brings up the individual's profile, profiles are linked to observations of that individual in the field notes window.

This activity addresses the following components of a conceptual ecology of evolution:

Variation within a population

A number of features of this activity focus students on the notion of variation within a population. First, observing variation in a population is made an explicit target of investigation through the question-based data query that presents "variation of structural traits" as a question dimension that can be asked with each of the three questions categories (see Figure 1). Second, the data view resulting from this query shows a population average as well as each individual point, identified by that finches' id number, so that students can see that each individual has a slightly different measurement (see Figure 2). These supports increase the likelihood that students will concentrate on variation in their investigations, and therefore they are more likely to raise this topic when they report on the history of their investigation and their findings in class discussions. Further, once variation is discussed, students will have a concrete shared experience to refer to in their discussions.

Role of variation in natural selection

Students are encouraged to consider both aggregate data (the population average) and individual data (noting the individual data points, and clicking on points to bring up individual profiles) throughout their investigation. This could help make students aware of individual differences as they identify population trends and changes over time. The computer environment provides a data log that automatically stores each of the observations students make. Students can organize and sort their evidence according to evidence categories pre-specified by the environment. One of these categories is labeled: "Differential survival -- data that shows that some individuals are less fit and die as a result of a selective pressure and that some individuals are more fit and survive (see Figure 3)." This can encourage students to reflect on individual differences in relation to survival during the course of their investigation.

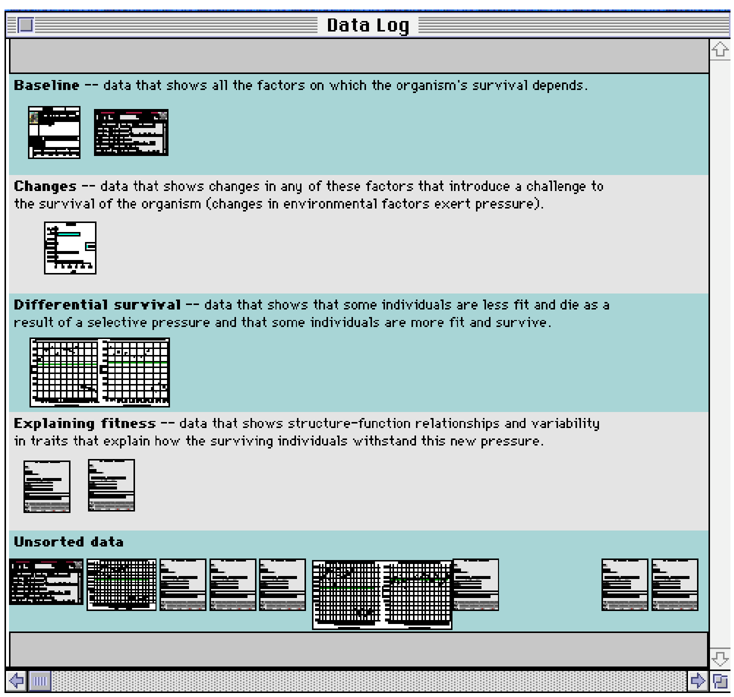

Figure 3: The data log where all student observations are stored. Students can categorize their data according to evidence categories pertinent to natural selection.

Evolution as changing proportions of individuals possessing particular traits

Encouraging students to recognize evolutionary changes as the changing proportions of individuals in a population possessing a particular trait is achieved by the same type of support available for encouraging students to recognize variation within a population. Changing distributions of a trait in the population are presented to students as a possible, explicit target of investigation through the question-based data query. This is represented by the questions stem "...distribution of structural traits?"

View of biological world

Students' views of the biological world are part of their conceptual ecologies and can affect the way they interpret evidence in their investigations. Many students may have a deterministic model for biological phenomena, in general, and for natural selection, in particular, expecting that knowledge of the "rule" governing a phenomenon enables you to predict the exact "outcome" of an event for each and every occurrence. However, many biological processes are probabilistic, that is, one can only predict the likelihood that a particular outcome will occur, but the actual outcome of any particular occurrence cannot be predicted. For example, in the Finch Scenario, students observe that beak size is related to survival. Students that maintain a deterministic view believe that finches that have a beak size greater than the population's average beak size will survive, they expect each and every surviving individual to have a beak size greater than average, and each and every dead finch to have a beak size smaller than average. Although this is an accurate trend, larger beaks only make it more likely that individual finches will survive, and there are some large beaked individuals that die. The data available in the Finch Scenario is based on published population data for finches in the Galapagos, and therefore reflects a probabilistic model, where students will encounter individual cases that do not fit the population trends they observe.

Complementary roles in fostering scientific conceptions of natural selection

Interactions with a rich, complex environment like the Finch Scenario, can result in localized understanding, students understand pieces of the process of natural selection, but are not able to put the pieces together to form scientific conceptions of the entire causal process of natural selection. Interactions with an idealized model, like the Natural Selection Simulation, can result in incomplete conceptions, because some details are omitted from the simulation, and it might be more difficult to relate processes observed in the simulation to actual phenomena. Working in both types of environments capitalizes on their advantages and compensates for their limitations. The two activities contribute to developing conceptions of the following components of a conceptual ecology of evolution in different ways:

Variation within a population

Both the Finch Scenario and the Natural Selection Simulation suggest that there are variations among individuals in a population. The combination of activities can help students elaborate their conception of variability within a population, because they interact with examples of discrete salient differences (i.e., coloration), as well as with examples of continuous, subtle differences (i.e., small differences in leg length).

Role of variation in natural selection

Each of the activities clearly depicts a relationship between variation and survival. The relationship between a particular trait and survival is more easily discerned in the Natural Selection simulation, because the only observable difference among individuals is the difference that determines survival. In the Finch Scenario individual finches vary along a number of dimensions, such as leg size and beak size, and it is not immediately obvious which dimension plays a critical role in survival. As a result, students working with the Finch Scenario are more likely to introduce this relationship as a topic for conversation. Students are more likely to discuss this topic, because it may be a source of confusion, since the relationship is less obvious, and because students are required to make a judgment concerning the significance of the differences for survival as part of their investigations.

Evolution as changing proportions of individuals possessing particular traits

The idea of evolution as the changing proportions of individuals possessing particular traits is easier to grasp and observe in the natural selection simulation. Students start the simulation with a variety of colors of beads on their cloth. After a few simulated generations students see a scene where the beads that remain on the cloth have a color that is similar to the color of the cloth, and the beads that are outside the cloth have different colors. The process that they simulate involves the relocation of beads to and from the cloth, and not on the transformation of beads. This can increase the likelihood that students will begin to associate changing numbers of individuals rather than change in individuals with the process of natural selection. However, it is not clear how easy or evident the transfer of knowledge is between this simulation and the real world. Students may understand the logic and the process depicted in the simulation, but may not relate it to real world organisms and events.

Students may not apply their understanding of the Natural Selection Simulation to the real world, because they may associate the phenomenon with characteristics of a classroom activity, rather than a simulation of nature. Although this activity accurately simulates some of the mechanisms that occur in nature, it is the student and teacher that have agency in this phenomenon and many aspects are "engineered" rather than randomly occurring – cloths are chosen, rather than an existing natural habitat, bead colors are chosen, rather than naturally occurring variations in organisms. Students may not necessarily understand or believe that the same processes apply to natural phenomenon in the same way (e.g., dots didn't choose to change, but animals might). In contrast, in the Finch Scenario students are merely observers of natural phenomenon and do not play a role in the unfolding of events. Therefore, the combined experiences of these two environments can communicate a desirable model of natural selection and facilitate knowledge transfer to real world settings.

Teleological conceptions of natural selection

Students tend to attribute need and volition to the process of natural selection. They state that individual organisms change, because changes in the environment created a need for a particular trait. Students may not have the opportunity to challenge this conception in the Natural Selection Simulation. Although the beads that represent individual organisms in the simulation do not change, students may not perceive this as inconsistent with the belief that animals change in response to need, because they are less likely to attribute intentionality to beads, and therefore this conception may not surface in the context of the Natural Selection Simulation.

View of biological world

Maintaining a deterministic rather than a probabilistic model of the biological world can interfere with scientifically accurate interpretations of evidence, and therefore, with the construction of more scientific conceptions of the process of natural selection through student-directed inquiry. Students are more likely to challenge deterministic models in their interactions with the Finch Scenario, because they are more likely to encounter individual data points that do not fit a trend they identified. Students may not attend to the fact that there are "camouflage colored" individuals in the Natural Selection

Simulation that were "hunted," attending to this information could challenge a deterministic model.

The Natural Selection Simulation does not emphasize the continual examination of individual data in conjunction with aggregate data, unlike the Finch Scenario that does emphasize this process through its variation view that represents each individual data point, and allows automatic links to individual profiles from the population view. Further, in the Natural Selection Simulation students may not be motivated to question the removal of "camouflage colored" beads from the cloth, or the retention of "non-camouflage colored" beads on the cloth, because of the nature of the two tasks. The Finch Scenario that involves synthesizing multiple pieces of evidence to construct a causal story may be more amenable to reflecting on individual pieces of data and considering how they relate to the overall process, while the Natural Selection Simulation that is perceived as an illustration may be more amenable to a global understanding of the process with less attention to particular details.

In the next section we will show some examples of how these two activities influence the topics of teacher-student discussions. These examples will also examine how these discussions can facilitate the process of acquiring new understandings.

Scientific Conceptions Permeating Discussions

Activities like the Natural Selection Simulation and the Finch Scenario may be designed to focus students on salient principles of the domain, or to guide students into particular ways of thinking about the domain. However, students may not reflect on their interactions with the activity and therefore may not realize these opportunities for learning (Roth, 1995). Classroom discussions, during investigation activities, or between activities can serve as prompts and venues for reflection, and help students realize these learning opportunities. In this section we provide a number of examples demonstrating how interactions with the Natural Selection Simulation and the Finch Scenario introduce different topics and insights as topics of discussion. These examples draw on observations and recordings from a number of participating classrooms. We ran our evolution unit in a total of 4 classrooms during the 1996-1997 academic year. The unit ran for 4 weeks in 3 classrooms, 1 honors and 2 regular at a local suburban high school, and for 6 weeks at a Chicago public school. We conducted more detailed observations and recordings of the discussions that took place in the Chicago school, and therefore, the majority of examples are drawn from that classroom.

Variability within a population

> [Teacher is observing a graph of either beak, wing or leg length with a group of students].
> **Teacher** - ... of the live ones, some have shorter, three have shorter and four have longer...

In this example we see that the data representation provides an opportunity to notice individual differences in the length of an organ. The students may not spontaneously attend to this information, but the teacher helps students realize this learning opportunity by directing their attention to these differences.

> [Students are working at the computer. They call the researcher over to ask how to select a particular view]
> **Student** - ....behavior of individuals? Well, uh, how can we get it all together instead of individuals?
> **Researcher** - You actually can't do it all together.
> **Student** - Because they eat different things? Because we looked at one and it said it ate spiders and then we looked at another one and it was eating seeds.
> **Student** - And we looked at a male and a female and the male was eating spiders and the female was eating seeds.
> **Student** - And another one was eating fruit.
> **Student** - So is it all females?
> **Researcher** - That's a really good question is it all females? So if we were on this island how would we know?
> **Student** - By watching them.
> **Student** - Observing.

In this example students have noticed that individual finches eat different types of food. This can be a first step toward recognizing that variation exists within a population. The students are looking for patterns between the type of food individuals eat and other characteristics, as a first step they wonder whether it is related to the finch's sex. This is a profitable strategy that can evolve into identifying structure-function relationships that can demonstrate the advantage of particular characteristics which is a central part of explaining a natural selection event.

Students' interactions with the environment, noting individual differences in structural characteristics, like leg size, as depicted in the first example, and noting individual differences in behaviors, as depicted in the second example, can help students reach a realization that individuals in a population vary. In the example below a student states that one of the things she learned from working on the Finch problem is that finches are individuals and they are different, even though they are all finches.

[The teacher is leading a culminating discussion on the Finch problem. The discussion started with students describing their explanation for why the finches were dying and what enabled the surviving finches to survive. Afterwards, at the point of the following quote, the teacher asks students what they learned from working on this problem].

Teacher - What else did you learn from working on these problems? What E?

E - That, like, finches they're all different, I mean some people can classify them like the same, and actually they're all different like different individuals.

Teacher - So before when you thought about finches maybe you just thought about little birds.

E- It was just all birds, and now ....[inaudible]

Teacher - And now you think of birds, and even other animals we don't understand real well as individuals, with individual characteristics?

E - Yeah.

It seems that the strategic support in the finch scenario is successful in focusing students on issues of variation, and that the data that students observe encourages students and teachers to discuss individual differences. The combined interactions with the Natural Selection Simulation and the Finch Scenario illustrate that variability exists, and the discussions that students engage in while they are interacting with these environments help them realize that variability exists within a population.

Role of variation in natural selection

The following sequence of class discussions shows how students acquire a more sophisticated understanding of the role of variation in natural selection. At first, students think of variation as a global, large difference, and advantage is related to size and strength. Students accept "bigger" and "stronger" as good explanations for advantageous traits, they do not see a need for specifying particular traits and for demonstrating the relationship between these traits and environmental constraints. A more sophisticated view would describe how a particular trait enables some organisms to better cope with specific constraints.

[Students and teacher are discussing the Natural Selection Activity that they completed in the previous class session. They discussed what each material in the activity represented and what happened in the simulation. Afterwards they try to link events that happened in the simulation to terms and concepts of natural selection. The teacher then asks students to try and apply what they learned to new settings].

Teacher - Now let me ask you a hypothetical question, what if it was something else [other than color]? What if it was something like shapes? How would that have anything to do with it?

Student - Same as color.
Student - Bigger.
Teacher - Bigger? What? The animals are bigger? All right, so what would the relationship...that might be an advantage...where do you think is a place that bigger animals would be better adapted to what kind of environment?
Student - Horse
Teacher - A horse? Why a horse?
Student - [inaudible]
Teacher - Oh, because maybe they're not the prey. OK that might be one. Bigger animals survive because why?
Student - They're stronger.
Student - Yeah, they wouldn't be eaten because nobody could...[inaudible]
Teacher - Bigger animals are stronger, so again like you said, the strongest survive. What about different environments? Be creative.

The Natural Selection Simulation that preceded this discussion helped students recognize that variation plays a role in natural selection. However, they are not concerned about the details of causality in this relationship. Such a concern does begin to emerge as students begin their investigations of the Finch Scenario (this is a problem that extends over a number of class periods).

After students had worked on their investigations of the Finch Scenario for two class periods, the teacher gathered the class for a whole class discussion. In this discussion the teacher asked students to share with the class what they had found so far. She also asked students to comment on each other's investigation approaches and findings. A number of students described that they saw different beak sizes and that they think that beak size is related to survival. One of the students in the class found this claim very disturbing. She states that she also saw that different finches had different sized beaks, but that she did not understand how beak size could affect survival. This is an important step in refining their understanding of the role of variation in natural selection. Some students now have a need for a more detailed description of the causal relationship between environmental constraints, differences in physical characteristics and survival. It is also important to note that while in the earlier discussion it is the teacher that initiates talking about the advantage of different traits, in this later discussion it is the students that raise this point, both in their investigation reports, and in their responses to other students' reports.

In a whole class discussion that culminates the Finch Scenario activity, students and teacher, together, describe a detailed causal explanation, relating beak size to a specific survival advantage:

[Students from different groups report on their final findings, the teacher synthesizes responses from the different groups and restates a common causal story. The discussion began with a description of environmental conditions that introduces a pressure].
Teacher: And that pressure selected what? This is where I'm not sure I understand. It selected what?
Students - [students call out responses, but it is hard to distinguish statements].
Teacher - The beak? It selected which beak?
Student - The longer.
Teacher - The longer beak. Now, I really get fuzzy -- why?
Student - Because the only food around was harder.
Teacher - The only food that was left during the dry season was hard?
Student - And it was hard to break open.
Teacher - And it was hard to break open. OK. And... finish the story...
Student - So the weaker ones...
Teacher - So the weaker ones, the weaker finches could what?
Student - The females and the younger ones had a hard time...
Student - Cracking
Student - Consumption went down
Teacher - How did you know that their food consumption went down?
Student - Said so in the field notes
Teacher - Said so in the field notes? OK. I just wanted to make sure you had some evidence for that. Did you all agree? You don't have to -- some of you told me about mating, some of you told me that you thought the beak length let them reach, reach higher, Se I think you told me that?
Student - Yeah
Teacher - Did you have evidence to support that?
Student - Yeah.
Teacher - What did it say?
Student - I don't know its not here.
Teacher - What do you remember?
Student - Something about reaching for the food.

This series of quotes showed a progression of refinements of students' conceptions of the role of variability in the process of natural selection. Following the Natural Selection Simulation students recognize that variability plays a role, but they regard variability as large, easily discernible differences. It is not clear whether this view of variability is a result of the representation of variability in the Natural Selection Simulation, where individual differences are striking, or whether this view of variability is a result of having experienced only a small number of examples of variability. Their later interactions with the Finch Scenario environment extend their view of variability to include more subtle differences in particular organs, such as differences in beak length.

This extension could be a result of increased experience with multiple examples of variability, or a result of the structure of the environment that encourages students to examine and compare specific physical characteristics, such as leg size.

Evolution as changing proportions of individuals possessing particular traits

The idea of changing proportions did not enter as a topic of discussion as well as variability. It surfaced once, somewhat indirectly, following the Natural Selection Simulation. In our analysis comparing the two activities, and the types of understanding they foster we proposed that the Natural Selection Simulation could be effective in illustrating and highlighting the idea of changing proportions of individuals. The following excerpt is from the Natural Selection culminating discussion:

> **Student** - It was the yellow dot that survived, right? And then it kept on reproducing yellow, yellow, yellow, yellow. They would all be yellow.
> **Teacher** - By the...you're saying that by the 3rd or 4th generation? OK, H is saying that in their case yellow survived more often, so she predicted that by the 3rd or 4th generation they would have a predominantly yellow population. Agreement? Or disagreement? Or questions?

The students' repetition of the descriptor "yellow" following their statement about the yellow dot reproducing could be interpreted as her stating that there were increasingly larger numbers of yellow individuals. This was the only reference to changing proportions in this discussion, despite the fact that the teacher encouraged students to pursue this topic further. Following the teacher's question about whether other students' agreed with this student's statement, the students took the discussion in other directions, focusing mostly on which colors were the colors that survived. Even after their experiences investigating the Finch Scenario, students still did not introduce changing distributions as a topic of discussion.

Although some of the supports available for focusing students on issues of variability in the Finch Scenario are the same as the supports available for attending to issues of changing proportions, the latter did not permeate discussions as well as the former. One of the reasons may be that students have to query the "variability of structural traits" question in the data-questions interface in order to obtain individual profiles. Therefore, students are likely to select this option even if at first they do not understand what it means or how it relates to investigating natural selection. However, the "distribution of structural traits" question is easier to avoid. One possible solution for future implementations of the curriculum is to explicitly prompt students to examine distribution views in their investigations and relate these observations back to their findings in the Natural Selection Simulation. Hopefully, once students begin to use the distribution views they will become a more significant part of class discussions which will, in turn, provide an opportunity for understanding how changing distributions reflect the process of natural selection.

View of biological world

In both schools we worked with, there were examples of students viewing biological phenomena as deterministic rather than probabilistic. The instances in which these views surface were very similar between schools. In each case, students had developed a theory regarding the quality of a trait that characterizes survival, then made an observation of an individual finch and found that it did not match their characterizations. Students were very disturbed by this finding and had a difficult time determining how to handle this conflicting evidence. They felt that the evidence had proved them wrong, but they were reluctant to abandon their theory, because they had found it very convincing up until the point where they observed that individual finch. Students in both schools asked for assistance when they confronted this dilemma. The following quote illustrates this interaction:

[Call the researcher over with a question]
C - We were looking at beak size dead and alive, and one of them had 11.9 and we're thinking when we look at the live ones that I mean 11 and above maybe they survive, 11 and below they die, but this one he's got 11.91(?) and he died. So...?
Researcher - So how would you explain that? Do you think you're wrong, or do you think there's a way to explain that, that you could be right and that could still be happening?
C - I think I'm wrong. But..., but, then why did he die? Cause his is basically normal to the rest, and the leg length is 18 point something, and that's just like the other ones that survived.
Researcher: -Well, is there anything just in day to day life that you know of or can think of where there's a trend or something you expect, or overall, but one or two don't really fit that?
BJ - Maybe somebody came with a big truck or something and ran over some of them...
C - Maybe, maybe [giggles]

This example shows that students' interactions with rich, authentic data, like the data available in the Finch Scenario, can help uncover conceptions regarding their views of the nature of the biological world. In contrast, interactions with abstract models, like the Natural Selection Simulation are not likely to uncover these ideas, because, by design, they eliminate subtle and peripheral features of a phenomenon in order to illustrate the essential components of the mechanism. Although students' alternative view of the biological world surfaced and became a topic of classroom discussions it was not resolved. In both schools, students stated that they understood that the fact that a single case does not match their prediction does not necessarily mean that they are wrong. However, it is not clear whether students actually understood and internalized this concept, and would approach subsequent investigations differently. Now that we have identified tools for challenging these conceptions, and making them a topic of discussion, we need to find ways to introduce new conceptions. More importantly, we need to identify activities that will help students realize the believability of probabilistic models, and their power to resolve these types of conflicts.

Conclusion

Students' interactions with activities that depict domain processes, and are scaffolded through domain-specific strategic support to focus students on key domain principles can create situations where students confront and challenge their initial beliefs. Teacher-student interactions play a critical role in making these concepts a topic of reflection and facilitating the process of developing scientific conceptions. Different activities afford different experiences and different types of understanding. In particular, rich simulations can help elaborate conceptions by reasoning through the subtleties and complexities of the real world. These rich environments may be more likely to help students develop robust scientific conceptions, because they draw on and confront students' conceptual ecologies and not just the conceptions relating to a particular topic or process. However, students might find it difficult to grapple with the complexity of these environments, and therefore may concentrate on localized inferences. Interactions with idealized models can help students view an entire causal process, and understand the interactions between causal components.

We demonstrated that interactions with both types of activities can introduce key concepts into class discussions. Student remarks in these discussions suggest that these activities and interactions are helpful in constructing scientific conceptions. We are currently in the process of analyzing pre- and post- measures in order to determine the extent of the effect of these types of interventions on student learning. We also found examples where important concepts did not permeate discussions, or that discussions about these topics were not effective for fostering new understandings. We need to characterize the interactions and supports that resulted in both productive and unproductive discussions so that we can develop a set of design principles for conceptual change learning environments based on student-directed inquiry.

Acknowledgments

This research is supported by a grant from the James S. McDonnell Foundation. Any opinions, findings, or conclusions expressed here belong to the authors and do not necessarily reflect the views of the James S. McDonnell Foundation. This work is part of the Biology Guided Inquiry Learning Environment (BGuILE) project. We thank William Sandoval for his collaboration on this research. We also thank David Goodspeed and Linda Patton for allowing us into their classrooms and collaborating with us as designers, and their students for their interest and cooperation.

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