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ABSTRACT

Building explanations is fundamentally what science is about. Students require support both for constructing their own explanations about the surrounding world, and for reflecting on those explanations in ways that help them to assess the quality of their explanations and the strategies they use to build them. This paper describes the development of a high school biology curriculum which integrates technological supports for explanation construction with scaffolded classroom discussion activities to support students' reflections upon their explanations as scientific artifacts. The goals of the integrated curriculum include developing students' ideas about the nature of scientific knowledge, their skills in conducting scientific investigations, and their understanding of core theories of biology. Data collected for the study of this project consisted of the students' explanations as they worked through problems. The explanations are examined on two broad dimensions: (1) the causal coherence of their explanations; and (2) how they use data to support their explanations. Contains 16 references. (DDR)

Evolving explanations in high school biology†

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Abstract

Engaging students in conducting their own scientific inquiry means engaging them in the construction of explanations about their world, because building such explanations is fundamentally what science is about. Students require support both for constructing their own explanations and for reflecting upon those explanations in ways that will help them to assess their quality and the strategies they use to build them. We are developing a high school biology curriculum which integrates technological supports for explanation construction with scaffolded classroom discussion activities to support students' reflection upon their explanations as scientific artifacts. Through this integrated curriculum we hope to develop students' ideas about the nature of scientific knowledge, their skills in conducting scientific investigations, and their understanding of core theories of biology. Using our software tool, ExplanationConstructor, students are successfully articulating coherent causal explanations for complex questions. Guided reflective discussions are encouraging students to evaluate their work according to how well they have used data to support their claims, and how well their explanations answer their questions. Yet, many students do not fully understand the criteria to which scientific explanations should be held, suggesting further work is needed to structure students' opportunities to reflect upon their work.

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Introduction

Engaging students in conducting their own scientific inquiry is to engage them in constructing explanations about their world. Building explanations is fundamentally what science is about (Mayr, 1988; Toulmin, 1953). This idea is often left out of science education (Kuhn, 1993). It does not seem reasonable, however, that students can acquire deep understanding of science and scientific inquiry without understanding its purpose. Yet, most students apparently lack both an understanding of the purpose of scientific investigation (Schauble, Glaser, Duschl, Schulze, & John, 1995), and the nature of scientific knowledge (Carey & Smith, 1995; Linn & Songer, 1993). An understanding of the nature of science and scientific knowledge, as reflected in the criteria to which scientific explanations are held, is crucial to being able to construct such explanations. Fundamentally, supporting students in performing their own scientific inquiry requires supporting them in their efforts to construct scientific explanations about natural phenomena while helping them to understand the purposes and goals for such explanations.

Our research is exploring how to provide support for students as they investigate and explain biological phenomena. We are developing a curriculum which integrates technological supports for explanation construction with scaffolded classroom discussion activities to support students' reflection upon their explanations as scientific artifacts. Through this integrated curriculum we hope to develop students' ideas about the nature of scientific knowledge, their skills in conducting scientific investigations, and their understanding of core theories of biology. We report here initial results from a recent trial of a unit on evolution designed for high school introductory biology courses. We broadly describe our approach, focusing specifically on a software tool, ExplanationConstructor, developed to support students' explanation construction as they explore computer-based investigation scenarios, and classroom activities designed to engage students in critical reflection of their explanations. Our initial results suggest that our approach is encouraging students to write and reflect upon scientific explanations. We close by raising some outstanding issues we are addressing in ongoing work.

Inquiry as Explanation

Engaging students explicitly in building their own explanations can help to frame the goals and processes of scientific inquiry. First, the explanatory task provides a framework for students to build deep understanding of a domain, and of scientific activity. By constructing explanations, students not only have to generate and interpret data, but have to move beyond local interpretations of data to synthesize conclusions from multiple data sources to support an explanation. Such explanations become artifacts for students' own reflection upon their understanding, and are available for discussion and critique. In our approach, such reflection and discussion is centered around students' explanations both as articulations of their domain understanding and as examples of scientific explanations generally. Thus, we engage students in assessing their work on each of these levels. This emphasizes how domain theories, as explanatory frameworks, satisfy more general goals for scientific knowledge.

We focus on two such general goals for scientific explanations, and engage students in critically evaluating their explanations according to these goals. The first is that scientific explanations should clearly articulate causal relations among the factors governing phenomena. Of course, while this is a general goal for scientific explanations, its satisfaction can be decided only with specific domain frameworks. To use an example from biology, the theory of natural selection is a framework for explaining how environmental factors influence an organism's behavior, and thus its structure. An explanation by natural selection therefore has to articulate how some environmental factor(s) require or allow some behavior, how some characteristic(s) of an organism differentially enables individuals to perform that behavior, and how such differences affect individual survival. Thus, a coherent explanation of some phenomenon by natural selection is evaluated according to these domain principles, as well as by the general criterion that causal relations be clearly articulated.

A second general goal for scientific explanations is that they account for observed data. Therefore, we focus students on using data they generate during their investigations to support their explanations. Again, what it means to account for data can be decided only with guidance from domain principles. Still, the general criterion that explanations be consistent with observed data provides a goal during investigations that can be formulated either as the need to state causal mechanisms which explain a pattern of data, or to find data that supports a particular explanation.

This combined focus on the degree to which students' explanations account for a specific situation according to relevant domain principles and how well these explanations achieve general standards for scientific explanations encourage students to see their explanations as examples of scientific knowledge. This abstraction should allow students to develop a more sophisticated understanding of the nature of scientific knowledge and strategies effective for producing that knowledge. By providing students with clear goals for their explanations, they can use these goals to self-monitor their progress through an investigation, and to direct their work towards satisfying their goals (e.g., searching for data to support a claim, or to enable them to draw a causal connection between factors).

Lastly, explanation construction frames the task of inquiry for students as the creation of a specific kind of product: one used to understand natural phenomena, and to communicate and convince others of that understanding. This framing provides a meaningful context for students to understand general investigative strategies that they can potentially learn through inquiry, but that many find difficult (see Table 1 for a few examples). For instance, students generally do not conduct controlled experiments (e.g., Klahr, Dunbar, & Fay, 1990), nor do they understand the reasons why they should (Schauble, et al., 1995). Controlled experiments are useful in science precisely because they allow causal relations between factors to be more accurately determined, and that is the reason such experiments are preferred over other approaches in the natural sciences. By making the goals behind inquiry explicit, we can engage students in a discussion of why strategies such as controlling variables are important for generating sound explanations.

Table 1. Approaches to supporting students through scientific inquiry difficulties

General Problem	Conflict withExplanation Goals	BGuILE Support
Failure to differentiate belief from support for that belief (Kuhn, 1989; Kuhn, Amsel, & O'Loughlin, 1988)	Clear articulation of causal relations Able to explain multiple situations	Separate explanation from data used to support it, and reflect upon why their explanations are good or bad
Confirmation bias (cf., Klayman & Ha, 1987)	Rule out alternative explanations	Rich problem contexts allow debate over alternative explanations
Ineffective experimentation strategies(Klahr, et al., 1990; Schauble, Glaser, Raghavan, & Reiner, 1991; Shute, Glaser, & Raghavan, 1989)	Clear articulation of causal relations among factors	Reflection that connects process to product

Thus, a central theme of our approach is to develop students' metacognitive skills for planning and conducting their own inquiry by engaging them in critical reflection around their created explanation artifacts. Such reflection should include not only a consideration of how well an explanation has accounted for a particular situation, but how well the explanation and the methods used to construct it meet more general goals for scientific work (cf. Gitomer & Duschl, 1995). For this reflection to effectively help students to abstract from their specific investigative experiences to broader understandings of the nature of scientific knowledge and inquiry requires that students have repeated and extended practice in building their own explanations. Further, such problem-solving practice must be interleaved with reflective activities within and across problems.

A Technology-Supported Design

Students require support both for constructing their own explanations and for reflecting upon those explanations in ways that will help them to assess their quality and the strategies they use to build them. We have developed a software tool, ExplanationConstructor, to support students as they build explanations for phenomena that they investigate through computer-based investigation environments. Critical reflection of the artifacts students build in ExplanationConstructor is modeled and scaffolded through structured classroom discussion activities. Our approach integrates computer-based investigations with whole class and small group discussions.

Specific investigation environments provide students with rich problems to be explained and in which several kinds of data can be generated to suggest and support explanations. The generation and interpretation of data is supported by domain-specific strategies embodied within each investigation environment (Tabak, Smith, Sandoval, & Reiser, 1996). In these investigations, students work in groups to answer an overarching question requiring explanation, and to generate explanations for this question and any sub questions they produce. Discussions are focused on students actively evaluating and critiquing their own and others' explanations. These discussions are geared both towards assessing students' domain understanding and their understanding of the rhetorical task of constructing a convincing scientific explanation. Students' computer-generated explanations serve as artifacts around which discussion takes place.

Students iterate through a cycle of investigation and discussion through several problems. Our current curricular unit on evolution spans three extended problems designed to occur over three to four weeks[1]. Each problem in the sequence is progressively more complex and open-ended. The first problem begins with strong guidance from the teacher, who models the kinds of question-asking and investigation strategies students will perform in subsequent problems. This first problem is also an opportunity to introduce students to the explanatory task they will perform throughout the sequence. By the end of the first problem students are working in small groups to construct an explanation for this constrained problem. Students continue to work in groups to solve the subsequent problems.

Building explanations

Students' work on their investigations is directed toward explaining overarching questions (e.g., Why are so many finches dying on Daphne Major, and why are the survivors able to survive?). Students work in groups to generate these explanations on the computer. Students are able to move flexibly between the specific problem investigation environment, where they generate and can record local interpretations of specific data, and our explanation support tool, Explanation Constructor. This integration of the explanatory task with the investigative task allows students to exploit the guidance offered by ExplanationConstructor while they are trying to solve the problem.

ExplanationConstructor allows students to organize their work around a set of questions they are trying to answer, and potential explanations for each question.

[1]The first two problems in this sequence concern marine iguanas and finches, respectively, on a Galapagos island. These environments have been developed by Iris Tabak and Franci Steinmuller. The third problem is about the development of antibiotic-resistance by bacteria, and is being developed by Renee Judd, Richard Leider, and the authors.

Students write their questions and explanations in an "Investigation Journal." The software supports students' explanation construction at both the domain and general levels by providing them with *explanation templates* of relevant domain theories. ExplanationConstructor also structures explanation construction to encourage students to write explanations that satisfy our general criteria for scientific work (causal coherence and support from data).

At the domain level, templates are simply explanatory frameworks that students can use to generate explanations for their questions. Each template is a series of components reflecting major causal relations within that framework. For example, the "selective pressure" template articulates the three major components that combine to explain the effects of a selective pressure on a population (Figure 1). Components are labeled with prompting sentence stems to guide students about aspects of the problem which need to be explained using that template. Thus, domain guidance is provided for students in the first place as they choose which template to use for their explanation. Each template has a description of the kinds of phenomena it can usefully explain, usually with an example. In selecting a template, then, students are able to focus on how to tell a particular story about the problem they are trying to solve.

Once selected, the structure of the template suggests what needs to be explained to make their selected story "work". This structure also guides students toward the data they need to generate to support their explanation. For example, the first component of the selective pressure template directs students to articulate some factor in the environment which can exert a selective pressure, thereby suggesting to students that they need to look at environmental factors. The second component requires that some organism be identified as being affected by these environmental factors, and that some specific cause of that effect be given. So, students are not merely guided to examine environmental factors, but to consider how those factors may be affecting some organism. For example, in the finch problem, students are asked to explain the difference in survival among finches. The "selective pressure" template thus suggests that they look for factors in the environment which might adversely affect the finches. Finally, the third component of this template directs students to relate individual structural differences to specific behaviors that enable or prevent survival in the face of the environmental pressure.

Templates thus suggest to students how the domain theory represented by a template can guide them to an explanation, and they are being explicitly encouraged to articulate causal connections between each component. This common form of templates, connected components, encourages students to decompose their explanations into specific causal relations, and to link each component together to tell an overall coherent causal story. This form is designed to help students construct explanations that satisfy the general goals for causal specificity and coherence.

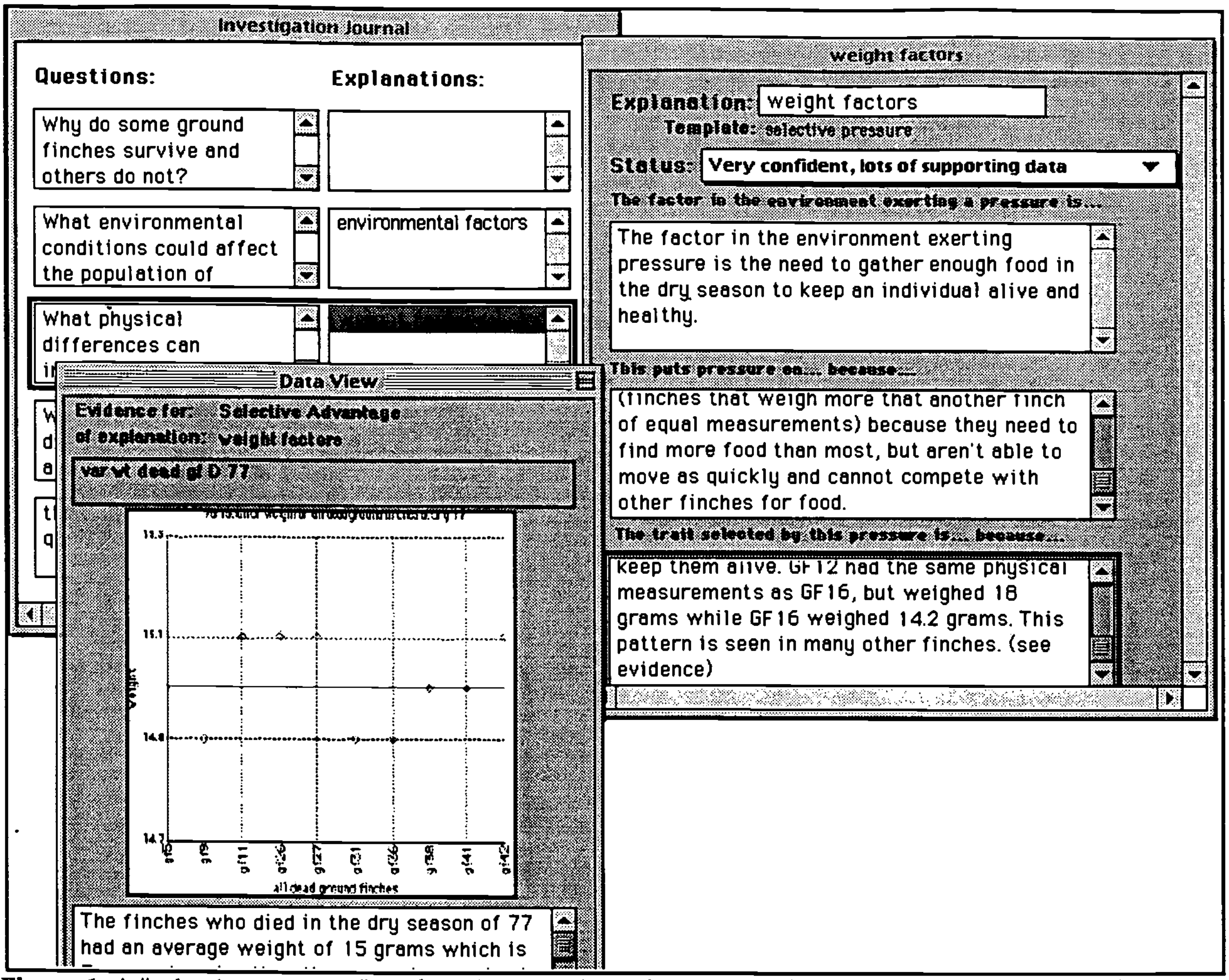

Figure 1. A "selective pressure" explanation template, showing student work from a recent study.

The template structure combines with domain-specific strategies embodied within each investigation environment to help students generate useful data, and provides a framework in which they can then interpret the importance of that data for their question. Students link specific data items to specific components of their explanations, and these are then displayed in the Data View. An annotation facility within the Data View encourages students to explain in more detail how each piece of data supports their explanation. Thus, students are not only engaged in generating and interpreting specific pieces of data as they conduct investigations, but they are integrating data sources to tell a coherent causal story. Students are explicitly encouraged to distinguish between the explanation they derive, and the data that it explains, satisfying the general goal of supporting their explanations with data. It is important that students link data to specific components, rather than to the explanation as a whole, because it encourages them to think about how data relates specifically to the explanatory framework embodied by each template.

Explanations as artifacts for discussion

This computer-based investigation is interleaved with classroom discussions about the explanations that student groups have constructed. Explanations are rich artifacts around which discourse can be organized. In our classroom trials to date, we have experimented with several different ways to center student discussions on their explanations along several dimensions. One immediate such dimension is how well a particular explanation accounts for the problem at hand. Does it satisfactorily explain this problem? Does it make sense according to domain theory? Other, broader criteria are addressed as well, including evaluating the clarity with which an explanation articulates causal relations among components, the amount and relevance of the data used to support it, the degree to which students have justified the relevance of chosen data to their claims, and how well an explanation maps into a chosen template.

Our goal for these discussions is to get students to focus especially on general aspects of their explanations. First, we want students to clearly articulate causal relations in their explanations. When causal relations are not clearly articulated, it remains unclear whether students are simply not expressing assumptions they hold about the problem at hand, or whether they do not understand the problem and their proposed explanation, or both. A central goal behind the design of explanation templates has been to encourage students to articulate causal relations, by decomposing such relations. Reflective discussions provide a way for students to assess how well they understand these relationships and how well they have stated them.

A second major goal of our design of these class discussions has been to foster an attitude in students that prefers explanations supported by data over unsupported explanations, however reasonable they may seem. We have found, unsurprisingly, that this is a difficult bias to overcome. By this, we do not mean that students are necessarily biased to believe their own hypotheses, but that students seem willing to accept an explanation that "makes sense", regardless of a lack of data to support it or conflicting data. Thus, we have focused class discussions very heavily on considerations of the data that students use to support their explanations, and why such explanations might be preferred over unsupported ones.

Students' cycles of investigation in our studies to date have been: initial investigation and explanation construction, inter-group explanation critiques, further investigation and explanation revision, and, finally, whole-class discussions to build consensus understanding of each problem. Students typically spend one or two class periods in each investigation phase, and one period on each discussion phase. During the group work phases of the cycle (the first three), the teacher circulates among groups to facilitate work. Researchers have also acted as facilitators during this work, primarily to offer technical assistance in the use of software, but also to facilitate investigation. The final consensus discussion is led by the teacher.

Formative Evaluations

We have just completed a classroom trial of the curriculum described above in three introductory biology classes in a suburban Chicago high school. Approximately 69 students are using this curriculum, 24 of which are enrolled in an honors level course. Detailed analyses of the data from this study are currently underway. We discuss here our current framework for evaluating the explanations that students construct using ExplanationConstructor, using examples from student work to illustrate performance differences. We also present excerpts from student discussions to suggest the kinds of discourse students engage in as they reflect upon their own and each others' work.

Qualities of students' explanations

A primary source of data from this study are the explanations student groups construct as they work through each problem. We have collected ExplanationConstructor journals for two separate problems from 21 groups across the three classes. We are examining students' explanations on two broad dimensions: the causal coherence of their explanations; and how they use data to support their explanations.

Causal Coherence

A central goal of this research is to understand and support students' construction of coherent, causal explanations for biological phenomena. To be causal, students' explanations must articulate specific cause-and-effect relations. To be coherent, such causal relations must be logically connected. An additional criteria includes the clarity of presentation. Ideally, causal relations and their connections should be explicitly stated, rather than needing to be inferred. Thus, from the students' point of view, we are asking them to perform two complex tasks: (1) investigate and derive a solution for a complex problem; and (2) articulate that solution as a coherent, causal account that is supported by data generated during the investigation. That is, understanding how much of what they've discovered about these problems should be included in an explanation, and the specificity with which it should be recorded, is itself a problem to solve. We are currently examining students' explanations to define and refine a coding scheme that can shed light on differences in students' understanding of this explanation task as we have presented it to them, and that can track changes in their performance across problems.

The task of constructing a causal explanation for a complex, unfamiliar situation is hard. Given that most students have had little practice producing such explanations prior to their experience with these problems, it may be unreasonable to expect most of them to write entirely coherent, causally articulate explanations without extended practice. As we have argued, explanation templates may make this task more manageable by suggesting to students how they can decompose (or compose) their conclusions to tell a coherent causal narrative about a phenomenon. Yet, in examining the explanations that student groups construct as they work through our two computer-based problems, it would be a mistake to judge students on their ability to map their explanations into particular explanation templates. Rather, their ability to do so probably provides some measure of the utility of explanation templates. To understand students' abilities to construct explanations, however, requires looking at their work more holistically. For a given problem, it may be necessary to combine several explanation templates to put together a complete picture of students' understanding of that problem.

In coding students' explanations, we derive from the text of specific explanations a network of causal relations (see Figures 2 and 3). The schematic network (Figure 3) represents the causal relations specified in the explanation and explicit connections between them, as well as any implicit connections that can be inferred. For example, the explanation in Figure 2 does not specifically state that the drought causes a lack of rainfall, but such an inference is obviously straightforward; these students clearly believe the drought to be the cause of the reduction in plants. This explanation is an example of fairly good student work in this study, but is not unrepresentative. This group has articulated a detailed causal story explaining a question that they posed as part of their investigation.

Some groups of students do not write detailed causal explanations within each template they choose (Figures 4 and 5). Reasons for this appear to vary considerably. In some groups, it is evident that as students move between examining data within the investigation environment and articulating their ideas in their ExplanationConstructor journals, their understanding of the problem progresses. In such cases, their explanations become more and more detailed and specific, and sometimes explicitly refer to earlier templates. In other cases, groups appear to be using templates as a means for considering alternative explanations to their questions. In these instances, groups appear to abandon explanations as soon as they believe them to be wrong. Both of these situations, using separate templates to tell different pieces of the overall story or using them to articulate competing hypotheses, suggest to us that the structure provided by ExplanationConstructor helps students to organize their thinking through each problem and work towards the articulation of an overall explanation.

Our analyses of the causal coherence of the explanations that students build using ExplanationConstructor are just beginning. Representing students' explanations as networks of causal relations allows us to evaluate the logical coherence of the stories they try to tell somewhat independently of the text itself. This seems to us to be the fairest way to minimize differences in students' writing abilities. Such representations also have the advantage of making more clear the causal relations that student believe obtain in a problem situation, and also allows us to represent the whole of students' arguments across the bounds of specific explanation templates.

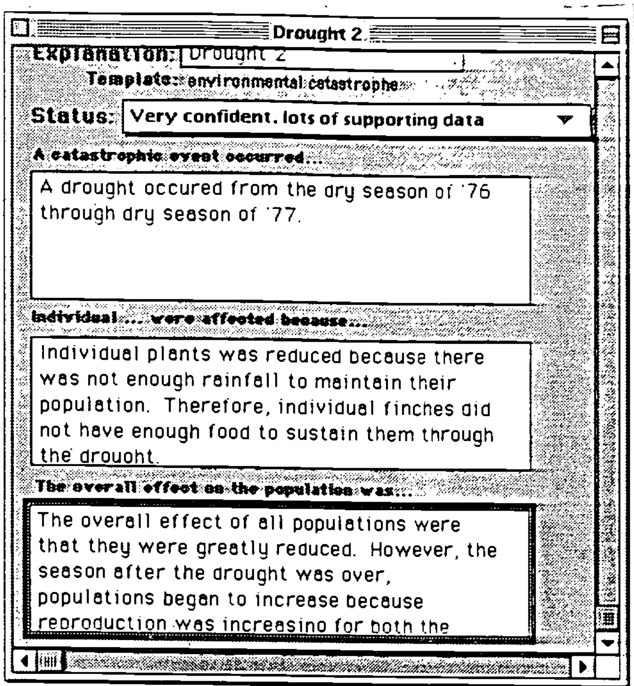

Figure 2. Example of a group's explanation from recent study. They have successfully written a causally coherent explanation within a template.

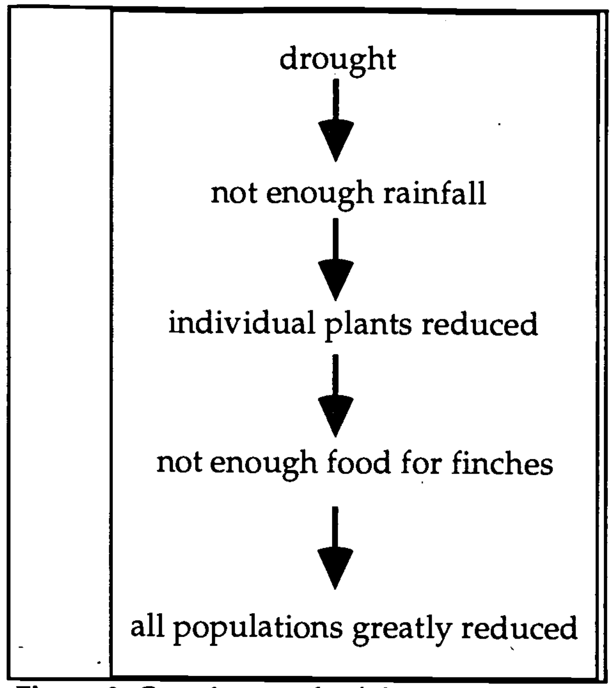

Figure 3. Causal network of the explanation in Figure 2.

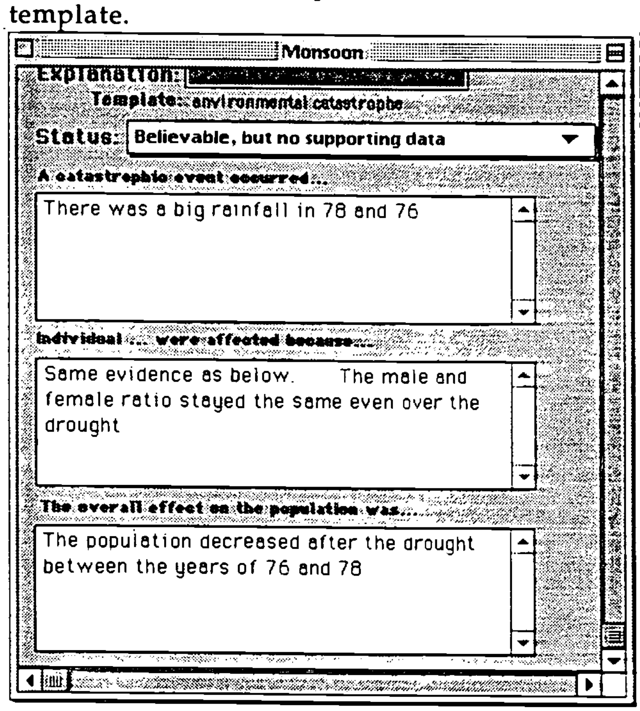

Figure 4. Another group's partial explanation of the same problem, with much less specification of causality

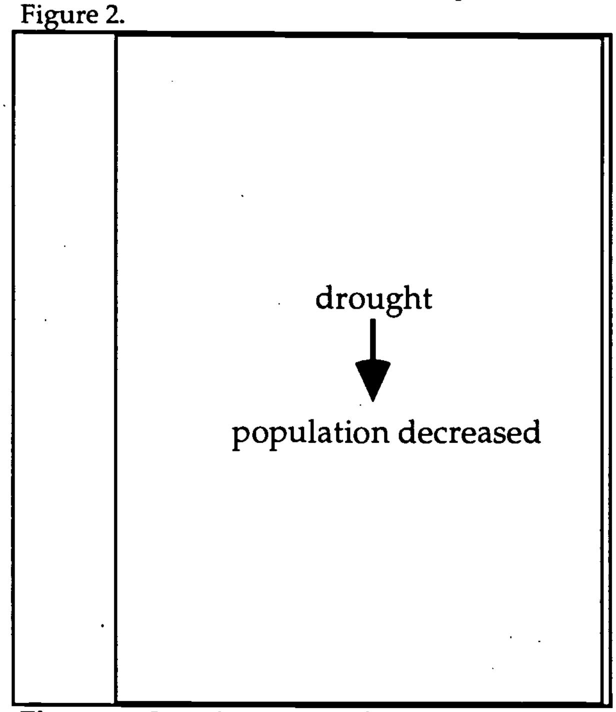

Figure 5. Causal network of the explanation in Figure 2.

Given this representation, of course, the obvious question is how it can help us to understand student performance. One thing that these representations of causal coherence show clearly are the disconnects within students arguments. They also show differences in the amount of specificity students provide in their explanations (e.g., compare Figures 3 and 5). In considering how one explanation is better than another, these two factors play related roles. That is, a lack of specificity can be seen as the omission of causal relations needed to connect two sides of a causal proposition. Thus, the explanation in Figure 2 articulates how a drought effects the finch population: by reducing their food supply. In contrast, the explanation in Figure 4 claims that the drought is directly responsible for wiping out the finches without some intervening cause. An issue for us as we continue developing this coding scheme is to try to understand whether such omissions are due to students' lack of understanding of the domain (i.e., what a drought is and how it could affect birds), or a lack of understanding of the rhetorical demands of writing a scientific explanation (i.e., are they claiming that the drought was directly responsible for the finch decline, or do they believe it to be the ultimate cause, and thus the important one to note).

Overall, our initial examination of students' journals for these two problems suggests that students were able to use explanation templates to articulate fairly detailed causal explanations for the overarching questions posed to them in each problem. There seems to be considerable variation in the amount that groups write and in the way they organize their investigation journals. Continued analysis should reveal differences in the causal coherence of groups' overall explanations.

Use of Data

Causal coherence is insufficient to produce a satisfactory scientific explanation. Such explanations should be supported by data. This means several things. It is not enough simply to cite data as evidence for a claim, although this is necessary. Such evidence has to be relevant to the claim. Furthermore, claims made from data should, ideally, include only valid inferences from that data (Kuhn, et al., 1992). We have preliminary impressions of students' use of data as support for their explanations, although we have yet to analyze this aspect closely. Students are citing data to support individual explanation components. The visual coupling of places to link data with explanation template components encourages students to link data to those components. Even without considering the quality of the data linked to each component, the fact that students are synthesizing data to support an explanation is an improvement over normal classroom discourse in which such arguments are rarely constructed (Kuhn, 1993). Further, such use of data provides the basis for student critiques of its relevance and sufficiency, and can help to expose a group's reliance on arguments based more on plausibility than on data. Thus, overall the explanation templates encourage students to begin to articulate explanations with a degree of specificity that allows for their assumptions and conceptions to be unpacked, and for their justified insights to stand out.

Students' linkage of data items to specific components is highly variable. Some components may have several pieces of data linked as supporting evidence, while others within the same explanation may have none. We are currently performing content analysis of explanations to understand why students choose to link data to a component or not. One possibility is that students may think certain claims are so obvious as to not require evidence. Another possibility is that students may be reluctant to abandon explanations that they believe account for some of the data merely because of a lack of evidence for some parts of the explanation. This is not an unreasonable strategy; there are certainly instances of scientific theories that have been argued without much empirical support. Indeed, Darwin's theory of natural selection may be the most famous example. Yet, one thing that careful scientists tend to do which these students have not, is distinguish between those parts of their explanations which are supported by data and those which are not, although they might seem reasonable.

Data Justifications

A widespread feature of groups' explanations is a general lack of justification for why data are relevant support for a claim. There are several potential reasons for this lack of justification. One reason is that in many cases students may simply feel it is obvious how data relates to their claim. For example, it seems redundant to explain why data showing a lack of rainfall is relevant support for a claimed drought; it is self-evident. There are, in fact, many cases where we have designed explanation templates to encourage fairly straightforward assertions, and these places are not coincidentally related to data available in our investigation environments. Thus, the lack of justifications, in itself, is not a major concern.

On the other hand, there are frequent cases where evidence crucial to establishing the causal link between an asserted cause and its effect is omitted by students, and the import of the data that they have linked is not explained. We believe that in at least some of these cases students may be assuming that the plausibility of their claim is sufficient justification for it, and therefore data to support it is not necessary. Of course, it is sometimes the case that support for an assertion is not available within the environment. For instance, a claim that longer legs enables finches to survive cannot be supported by data, because it simply is not the case. There is no data to be found that could support that claim. And that, of course, is exactly the point. Regardless of their failure to find supporting data, and perhaps because of the lack of directly contradictory data, students appear content to let their arguments rest on their apparent plausibility. In many everyday situations this kind of reasoning may suffice, although it fails to meet scientific standards for explanation. We emphasize this point especially to suggest that simply constructing explanations, regardless of the support for that process, is not enough to develop students' abilities to improve their explanations. Reflection upon the quality of their explanations appears necessary.

Critical Reflection

We have designed three kinds of activities to engage students in critical reflection upon their work. Midway through an investigation groups critique each others' work, thus giving groups the opportunity to address critiques during further investigation. Critiques also occur after an investigation. Individual students have also made self-assessments of their work, in which they are explicitly asked to rate themselves according to general criteria. The third kind of activity is a whole-class consensus discussion at the end of every problem designed to help students think about how their work on a specific problem is related to the theme of the unit: evolution by natural selection.

Critiques

For the critique activities, students are given specific question prompts to ask of their classmates (example questions are, "Does this explanation account for all of the available data that is relevant to this claim?"; "Is there data that poses problems for this explanation that needs to be considered?"). These questions are designed to encourage members of different groups to debate the merits of their work and suggest areas where groups need to do more work. The success of these critiques has been quite variable, and appears to depend heavily on the composition of the groups. In cases where one group has made much more progress on their investigation than another, the critiques become more like tutorial sessions. The dominant group will explain their explanations, point out their data, and suggest to the other group what they need to do to arrive at the same conclusion.

In other cases, members of different groups push each other to justify why they believe their explanations, and specifically ask for evidence. Interestingly, demands for evidence appear to be tied to students' judgments of the plausibility of assertions, instead of some general criterion that assertions need to be supported by data. Consider the following example. NS (students are denoted by first and last name initials) is asking the members of another group to give their best explanation for the finch problem. The double slash marks (//) indicate where students are interrupting each other.

EH: We have two explanations why some finches could adapt. One reason is their beak size. Certain finches with certain beak size could eat the plants that did die; and certain finches were just smarter than other finches.
NS: Intelligence!
EH: Yea, exactly. cuz one of, like, there was one, like...//
NS. //I have a question.
EH: What's your question?
NS: Where did you get this evidence for the intelligence?
EH: It was from the field notes//
FS: //No, no, we don't have any evidence for that part//
NS: //they've, like, taken standardized tests, like//
JH: //No, no! they stand behind other finches and take the food.
EH: Yeah.

NS: Oohhhh!.

The first claim, that beak size determines survival goes unchallenged, while the assertion that some of the finches are smarter than others is met with outright skepticism. NS clearly does not think that one could tell which birds are smarter than others, so she demands evidence for this claim. When the group provides a piece of data (a field observation note they retrieved in the investigation environment describing one bird stealing seeds from another), NS becomes satisfied. The initial claim about beak size, although neither EH nor his group mates have specified the "certain beak size", is never challenged in subsequent dialogue.

This notion that plausibility is as sufficient a justification for believing claims as having data to support them is consistent with some of the groups' explanations, as discussed above. It suggests to us that we have not yet succeeded in helping students understand the value of searching for data to support ideas that you are already inclined to believe. Of course, in science such skepticism is valued precisely because our inclinations are so often wrong. The task for us, then, is to explore ways to push students to be skeptics even when a proposed explanation appears reasonable.

Self-assessments

We ask students to assess themselves on four criteria at the end of their investigations: (1) the sufficiency of their data to support their explanations; (2) the relevance of their data to their explanations; (3) the clarity with which their explanations state cause-effect relations; and (4) whether they have considered alternative explanations. By and large, these questions do not seem to elicit deep responses from students. Indeed, their responses suggest instead that they do not really understand what we are asking them to assess. Far and away, the most common answers to the first two criteria are to the effect, "our data is relevant because they support our explanation." Such a straightforward response certainly answers the criterion quite directly, but it unfortunately lacks any information about why students feel their data supports their explanation. Kuhn (Kuhn, 1989; Kuhn, et al., 1988) has shown that children often have trouble distinguishing between theory and evidence, and that may be the case here. Thus, the students in our study may not make a distinction between the explanation they have constructed and the data that it purports to explain. In that case, they may very well not understand what it means to assess the relevance and sufficiency of their data.

With our other assessment categories we see similar responses, although at least assessments of causal articulation show a range of responses which indicate that some students understand the task as applying general criteria to their specific explanation. That is, the answers that we value for these assessments are not vague tautological ones, but rather should demonstrate how students' specific explanations meet these general criteria. It may be the case that simply performing such self-assessments is of benefit to these students (see White & Frederiksen, 1995), although our analyses of such effects are in progress.

Consensus discussions

The third kind of discussion activity we have implemented are whole-class consensus-building discussions following each problem. By design, these discussions are led by the teacher and focus on two things: 1) constructing, as a class, a single consensus explanation for the problem; and 2) relating the specific problem back to the content theme of the unit: evolution by natural selection. Following their explanation construction, students have been highly engaged during these discussions. One positive outcome of these discussions is that students are citing data they have generated and interpreted to support their ideas for what belongs in the consensus explanation. Also, where disagreements have arisen, students mostly counter-argue by appealing to their data, rather than strictly on their beliefs. Students also explicitly use their understanding of the particular problems they have investigated to articulate their understanding of the content themes of the unit. For example, students have repeatedly appealed to aspects of the finch situation as illustrating the effects of environmental pressures, or the effects of individual variation. Although detailed discourse analysis of these discussions has not been completed, these signs suggest to us that these discussions are providing additional useful opportunities for students to articulate their understanding, especially of the domain.

Conclusions

We have argued that support for students' scientific inquiry requires support for their construction of explanations of complex phenomena. Framing inquiry as the task of constructing explanations provides a meaningful context for the development of general investigative strategies held valuable by educators and researchers. Specific explanations can also serve as powerful artifacts for student reflection. This reflection can and should occur on many levels. At one level, students can evaluate their explanations in terms of their accuracy in accounting for the phenomena under study. Such explanation construction and reflection can strengthen students' understanding of core domain theories.

On another level, students can consider their explanations as examples of scientific work. This enables them to enter into the discussion of what is considered valuable in such work. By understanding and appropriating criteria to apply to scientific explanations, students can use them to evaluate both the explanations they create and the processes they have used to generate them. Ultimately, such experiences can enable students to feel a part of a larger scientific community, and may help them to see science as the dynamic, social, and subjective enterprise that it is: people trying to understand the world in which they live.

Although analyses of our data are ongoing, our preliminary findings suggest that students are able to take advantage of our environment to articulate scientific explanations for complex phenomena. Using our scaffolded software, students are able to articulate causal relationships that explain observed patterns of data, and they are able to cite data to support their assertions. Many of the explanations that student groups produce are causally coherent accounts of the problem phenomena they have been asked to investigate. Yet, simply building explanations is insufficient for students to develop their abilities to build good ones; they need to be supported through the process of reflecting upon what makes their explanations good or not.

Our results so far suggest that we have only partially succeeded in helping students understand some of the rhetorical aspects of building scientific explanations. Students do not always appear to understand the importance of clearly articulating causal mechanisms, for example, or of justifying the relevance of data used as evidence. Instead, they seem content to leave such things implicit. Further, they do not consistently apply general criteria for scientific work to their own explanations, oftentimes omitting evidence for assertions because they seem plausible and reasonable.

We believe that the most crucial factor to improving students' understanding of the purposes behind their explanations, and thus the criteria they hold for them, is providing them with more opportunities for reflection, and providing better structure to those opportunities. We are currently exploring the right level of specificity of prompts that can guide students toward these criteria. Also, we think that by more explicitly focusing students on the commonalities and differences between explanations for different problems we may be able to help them construct a generalized understanding of scientific explanation. As we build students' understanding of how to assess the products of their inquiry, their explanations, we can begin to support their reflection upon the strategies they use to produce these products. In this way, not only can we help students understand the nature of scientific knowledge and inquiry, but help them develop the reasoning skills they need to perform their own.

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