Why Scaffolding Should Sometimes Make Tasks More Difficult for Learners

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ABSTRACT

There has been much interest in using software tools to scaffold learners in complex tasks, that is, to provide supports that enable students to deal with more complex content and skill demands than they could otherwise handle. Many different approaches to scaffolding techniques have been presented in a broad range of software tools. I discuss two mechanisms to explain how software tools can scaffold learners. Software tools can help structure the learning task, guiding learners through key components and supporting their planning and performance. In addition, tools can shape students' performance and understanding of the task in terms of key disciplinary content and strategies, thereby problematizing this important content. While making the task more difficult in the short term, by forcing learners to address these ideas, such scaffolded tools make this work more productive opportunities for learning.

Keywords
caffolding, interactive learning environments, science education

INTRODUCTION

There is much interest in education reform in using technology to support learners. One aspect of the argument for technology has been that software can be used to *scaffold* students, that is to provide enough support to enable learners to succeed in more complex tasks, and thereby to extend the range of experiences from which they can learn (Davis & Linn, 2000; Edelson, Gordin, & Pea, 1999; Guzdial, 1994; Quintana, Eng, Carra, Wu, & Soloway, 1999; Reiser et al., 2001). Scaffolding is a key element of the notion of cognitive apprenticeship, in which students can learn by taking increasing responsibility and ownership for their role in complex problem solving, with the structure and guidance of more knowledgeable mentors or teachers (Collins, Brown, & Newman, 1989).

There are many different approaches to scaffolding, and no common framework has yet emerged that can be used to provide design guidelines for scaffolded software. In this paper, I propose two general mechanisms by which software tools can shape tasks for learners in a way that makes their problem solving more productive, and thereby scaffolds their learning.

Traditional Approaches to Scaffolding

The term *scaffolding* has traditionally been used to refer to the process by which a teacher or more knowledgeable peer assists a learner, altering the learning task so the student can solve problems or perform tasks that would otherwise be out of reach. The conception is associated with Vygotsky's notion of the zone of proximal development, which characterizes the region of tasks between what the learner could accomplish alone and what he or she could accomplish (and master) with assistance (Rogoff, 1990; Vygotsky, 1978). It is important to stress the dual aspects of both (a) accomplishing the task and (b) learning from one's efforts, i.e., improving one's performance on the future tasks in the process. If learners are assisted in the task but are not able to understand or take advantage of the experience, the assistance will have been local to that instance of scaffolding, but will not have provided support for learning. Thus, scaffolding entails a delicate negotiation between providing support while continuing to engage the learner actively in the process (Merrill, Reiser, Merrill, & Landes, 1995).

In recent design research on interactive learning environments, this notion of scaffolding has been generalized to refer to aspects of software tools that assist the learners in making progress on what would otherwise be tasks out of their reach. Software scaffolding provides some sort of structure that helps make the learning more tractable for learners. For example, the software might provide prompts to encourage or remind students what steps to take (Davis & Linn, 2000), graphical organizers or other notations to help students plan and organize their problem solving (Quintana et al., 1999), automatic execution of lower level processes, or representations that help learners track the steps they have taken in the problem solving process (Collins & Brown, 1988; Koedinger & Anderson, 1993). In all these cases the software provides additional assistance beyond what a simpler, more basic tool would have provided, to allow learners to accomplish more ambitious tasks.

This work on scaffolded software tools has been very encouraging, and promises to be an important benefit in integrating technological tools into classrooms. However, there have been a wide range of approaches to designing software scaffolds, and almost as many design principles as there are working systems. Development of general guidelines for the design of

software scaffolds first requires a general theoretical framework to characterize how tools can scaffold learners. How can we characterize the mechanisms by which software scaffolds assist learners?

There are a number of different ways one could carve up the space of software scaffolds. We could attempt to organize scaffolds according to the nature of the interface feature involved, such as text-based prompts, or hyperlinked representations. We could enumerate different functions scaffolds can serve, such as linking representations or helping learners break down complex processes into their subcomponents. Such analyses have clear utility. However, a principled articulation of scaffolding approaches must begin with a model of the task and the identification of the obstacles that learners face in performing the task (Quintana, 2001; Quintana et al., 1999; Reiser et al., 2001). A delineation of scaffolding strategies must be based on an analysis of what the target domain requires of learners, why the task is difficult, and finally how interacting with the tools can help learners overcome these difficulties, both to accomplish the task and to learn more effectively from the experience.

In this paper, I argue that there are two principal mechanisms by which software scaffolds can assist learners in mastering complex tasks. Following discussion of these two scaffolding mechanisms, I present some specific design principles consistent with this model, and describe their implementation in learning environments. To construct this argument, I will focus on scaffolding in the discipline of science. Much of the work on scaffolding tools has taken place in this domain, and there is a rich literature on the obstacles learners face. Furthermore, tools to access and interpret data are a central part of scientific investigations, so this domain is a productive context in which to explore the design of scaffolded tools.

THE NEEDS OF LEARNERS

Modern instructional approaches in science and mathematics emphasize learning by engaging in knowledge construction practices. In the case of science, this entails learning in the context of scientific investigation and argumentation (Edelson, 2001; Olson & Loucks-Horsley, 2000; Singer, Marx, Krajcik, & Chambers, 2000). These investigations often entail students learning general principles in the context of specific problem scenarios. Designers have developed approaches of problem-based learning (Cognition and Technology Group, 1990; Schank, Fano, Bell, & Jona, 1994; Williams, 1992) and project-based science (Blumenfeld et al., 1991) as a way of engaging learners in acquiring disciplinary knowledge in the context of solving particular problems, such as learning genetics by working through the tasks of being a genetic counselor (Bell, Bareiss, & Beckwith, 1994) or learning introductory physics by analyzing the quality of air in one's community (Singer et al., 2000). These approaches, while providing the potential to connect knowledge more effectively to real world contexts, also pose a particular type of challenge for learners. For this approach to be successful as a learning approach, students must not only construct solutions to the particular scenario, but must construct and analyze their solutions in terms of more general disciplinary content. In particular, students need to ground their reasoning in more general disciplinary strategies, and connect the explanations or arguments they construct to more general disciplinary frameworks. For example, if students are learning about mass and density by designing toy boats to carry loads, they need to analyze and synthesize their results and work toward physical explanations, rather than focusing only on the goal of the boat-building task (Schauble, Klopfer, & Raghavan, 1991).

Performing an investigation is a complex cognitive task that pushes the boundary of learners' content knowledge and processes. For example, the current education standards characterize the iterative processes of designing an investigation, collecting data, constructing and revising explanations based on data, evaluating explanations, and communicating arguments (Olson & Loucks-Horsley, 2000). This requires coordinating domain-specific processes and content knowledge, and metacognitive processes to plan, monitor, evaluate and revise these investigation plans. Thus, learners face challenges at several levels. The knowledge students are mastering includes conceptual knowledge, basic domain process skills, domain-specific strategies, and more general metacognitive processes.

Along with efforts to bring more ambitious science practices into classrooms, there has now been a rich set of empirical studies documenting the challenges that learners face. We briefly consider the main findings here in order to motivate the nature of the solutions that scaffolds can provide to these problems. Where does the complexity arise for learners in science?

Tacit expert knowledge: Sophisticated problem solvers relies on strategies for planning and guiding the reasoning. These heuristic strategies in science are needed to plan investigations, select data comparisons, and synthesize findings. These strategies are built upon on discipline-specific explanatory frameworks (Reiser et al., 2001; Tabak, Smith, Sandoval, & Reiser, 1996). A key challenge is that this knowledge is typically tacit for more experienced reasoners, and very much taken for granted. Instruction often fails to make these strategies explicit for learners.

Non-reflective work: Learners tend to focus on products rather than on explanatory and learning goals (Perkins, 1998; Schauble, Glaser, Duschl, Schulze, & John, 1995). The difficulty in managing investigations leads to little attention being given to reflection and reevaluation (Loh et al., 2001). Lack of content knowledge further complicates the process of evaluating the progress of an investigation.

Fragile and superficial understanding. Learners tend to focus on surface details, and have difficulty seeing the underlying structure (Chi, Feltovich, & Glaser, 1981). They may have difficulty mapping between related representations and instead become overly reliant on particular forms.

In summary, the task demands of engaging in scientific investigations reveal a system of challenges for learners. The ongoing cycle of planning and monitoring, sense making, and communication requires a number of processes that are likely contexts where assistance will be needed. Investigations require planning, in which students need to coordinate reasoning about hypotheses and reasoning about experiments or data comparisons that can be constructed to test hypotheses (Klahr & Dunbar, 1988). Constructing and pursuing that plan requires new disciplinary strategies, and poses metacognitive demands in continually monitoring, evaluating and revising that plan. In addition to help in managing this process, learners may need assistance in thinking through their own solutions in terms of the disciplinary content, so that they can learn about the discipline from the experience. Making sense of the data collected may require deep subject matter knowledge to interpret observations in light of disciplinary frameworks. Learners may need prompting to consider alternatives in light of initial support for a line of argument. They may need assistance in exploring the implications of the evidence they collect for the hypotheses they consider. They may not articulate their ongoing understanding, focusing instead on pragmatic goals of creating required products. They may need assistance in scientific discourse to move beyond description and communicate a scientific argument. In all these processes, the challenges of more superficial understanding, lack of access to tacit expert strategies, and a tendency toward non-reflective work create the need and opportunities for more supportive environments.

HOW CAN TOOLS HELP LEARNERS?

While traditional views of scaffolding have focused on social interactions as the source of assistance, the focus of the last two decades of research on the cognitive science issues in technology design has illuminated ways in which technological tools may provide some types of scaffolding functions. In considering how to help learners with these challenges, it is important to reconceptualize the learning problem from that of an individual working on tasks, perhaps with assistance of another more knowledgeable other, to focusing on the context in which the people are acting, the tools they use, and the knowledge embedded in this context. Rather than considering what the individual can accomplish, this view of distributed cognition focuses on what the system of person and tool can accomplish (Hollan, Hutchins, & Kirsh, 2000). The structure of a tool shapes how one interacts with the task and affects what can be accomplished.

One clear possibility for more supportive tools lies in automating aspects of tasks, and thereby restricting the part of the task for the learner needs to perform, potentially enabling them to focus on more productive parts of the tasks (Salomon, Perkins, & Globerson, 1991). This is the perhaps the most straightforward sense of scaffolding. For example, calculators can offload simple computations, allowing people to focus on other parts of the data manipulation tasks, such as considering what calculations to compose together to solve a problem. Word processors with spelling checkers can allow writers to focus more on the construction of their prose rather than devoting time to checking spelling in dictionaries. If offloading these aspects of the task enable learners to focus more effectively on the conceptually important aspects, and thereby learn from their experience, the tool has scaffolded that learning.

Tools can have even more dramatic effects on tasks in the way they shape the task itself. In fact, the nature of the tools we use can be a critical factor in how people think about the tasks they perform (Hutchins, 1995; Norman, 1987). This is particularly true when tasks involve accessing, manipulating, storing, or reasoning about information. Norman (1987) describes *cognitive artifacts*, or tools that are used to represent and manipulate information in a task. These tools can change the task in fundamental ways. The cognitive artifact becomes the vehicle through which the person interacts with the environment. It provides the representation of external states and the vehicle for manipulating the environment. Because of the central role of tools in effecting actions in information domains, the task cannot really be defined independent of the tools people use in the practice of that task (Bannon & Bødker, 1987). Thus, the nature of the task emerges from the interactions of people, subject matter, and tools, and the nature of the tool clearly affects how tractable the performance of a task is for learners.

Norman describes the problem of mapping between the external representation and what it represents. The goal of human-computer interaction design research is to make that mapping as transparent as possible. Cognitive artifacts can change the task for users in the way in which they represent and allow people to manipulate information. For example, direct-manipulation interfaces allow users to control a process by appearing to act upon it directly, through the visual metaphor (Hutchins, Hollan, & Norman, 1986). Visualization tools are designed to help users form deep models of an underlying system (Hollan, Bederson, & Helfman, 1997).

In the design of scaffolded tools, we can use this mapping to our advantage. Rather than striving only for transparency between the representation and the world it represents, we can bend that representation to instructional purposes. Cognitive artifacts provide a lever for designers to shape how learners think about tasks. In the next section, we consider how cognitive artifacts can be used to instructional advantage.

MECHANISMS OF SCAFFOLDING: STRUCTURE AND PROBLEMATIZE

How can tools provide scaffolding? First, let us revisit the definition of scaffolding as applied to science. There are two critical notions in scaffolding: (1) learners receive assistance to succeed in more complex tasks that would otherwise be too difficult; (2) learners draw from that experience and improve in process skills and/or content understanding. Focusing on the representational properties of tools puts us in a position now to consider how the specific design of the tool can support learning tasks.

I propose two complementary aspects of scaffolding in software tools — it can help structure problem solving, and it can provoke learners to devote resources to issues they might not otherwise address. We consider each of these in turn.

Structuring the Task

The first sense of scaffolding is the most straightforward — if reasoning is difficult due to complexity or the open-ended nature of the task, then one way to help learners is to make the task more structured. This may be done by providing structured workspaces, graphical organizers, decomposing functionality according to conceptual processes, or providing prompts. The structure of the tool may provide guidance as to what actions to take, their order, necessary aspects of work products, and so on. This type of structuring is a key characteristic of a number of different scaffolding approaches. For example, in KIE, structured prompts reminds students of aspects of the process they may otherwise neglect to perform (Davis & Linn, 2000). Model-It structures the task of modeling into plan, build, and test processes, and organizes relevant functions in each of those modes (Jackson, Krajcik, & Soloway, 1998). In the BGuILE ExplanationConstructor, structured workspaces can be used to remind students of the necessary components of their explanations, and can remind students about the criteria they should apply to evaluate their own work (Reiser et al., 2001; Sandoval, 1998). In these cases, the scaffolded tool addresses the obstacles of the investigation task by helping learners construct their plans, consider the possible actions relevant to each stage of the process, monitor the plan, and tie in relevant disciplinary ideas as they make sense and communicate about their data.

Problematizing Concepts

The second general approach is to make something in students' work more problematic (Hiebert et al., 1996). That is, the software tools help students see something as problematic that they might otherwise overlook. Rather than simplifying the task, the software forces students to encounter important ideas or processes. For example, if students are forced to use a menu to categorize the data they have collected, they need to consider the significance of the data. In the BGuILE ExplanationConstructor (Sandoval, 1998), students must make conceptual distinctions between the type of argument they wish to construct. In these cases, forcing students to apply these distinctions, which represent key conceptual ideas in the target discipline, can provoke debate, deliberations, and decisions that are all productive for students as they make sense of the findings of their investigation and manage its progress.

In this way, scaffolds can provoke students, "rocking the boat" when they are proceeding along without being mindful enough of the rich connections of their decisions to the domain content. This provocation may occur as the tools force them into decisions or commitments required to use the vocabulary and machinery of the interface. This type of scaffolded tool may create short-term costs, preventing students from rushing through their work in a problem without being mindful of the subject-matter issues that are the goal of the instruction. While this may be a short-term challenge rather than directly assisting with more expeditious solutions, such a tool may make the students' efforts in the problem a more productive learning opportunity.

The social context of collaborative problem solving is often integral to the problematizing nature of the tool. Students must make their understanding public when using tools that represent conceptual distinctions explicitly. Such tools require students to discuss disciplinary ideas decisions in order to effect actions in the tool. In this way, the artifact students use to examine data and record their interpretations becomes a vehicle for negotiation of understanding about the disciplinary ideas and their application to the task at hand (Roschelle, 1992).

These two mechanisms of structuring and problematizing are often complementary. The same characteristic of a tool designed to help structure students' engagement in a task, for example, by providing guiding prompts or making explicit a set of subtasks, may also problematize the disciplinary ideas, by requiring students to make sense of the options and connect their own work to these disciplinary ideas.

In summary, through these two mechanisms, scaffolds can help learners overcome some of the challenge of the complexity in the domain. Their work can be more productive and more effectively guided by expert strategies and understanding. In the next section we provide examples from our work on BGuILE learning environments that exemplify these complementary functions of guiding and problematizing in students' scientific investigations.

DESIGN PRINCIPLES: USING TOOLS TO MAKE THE TASK EXPLICIT

The design principles I present here address the learner obstacles of fragile understanding and accessing tacit expert knowledge. The key to the design approach is to help make the structure of the task more accessible to learners through the

tools they use and the artifacts they create. Articulation plays a central role in the approach. We will help learners understand the tasks by requiring them to articulate their actions and encode their results in terms of disciplinary frameworks.

I will present two types of designs that attempt to help students understand and practice these investigation and argumentation strategies by making them explicit in both the tools students use and the work products or artifacts they create. We call these *strategic tools* and *strategic artifacts* (Reiser et al., 2001). I describe these two types of design features and then present examples of scaffolded tools that employ these strategies.

Strategic Tools: We structure the tools students use to access, analyze, and manipulate data so that the implicit strategies of the discipline are visible to students. When students interact with these tools they are led to articulate their interaction in terms of these strategies. For example, when students construct data queries they articulate their query in terms of the key distinctions in the types of comparisons used to build theory in the domain, rather than solely in terms of surface data parameters.

Strategic Artifacts: We design the work products that students create to represent the important conceptual properties of explanations and models in the discipline. For example, we have students construct hypermedia documents that make explicit the rhetorical structure of their arguments.

Figure 1. The query screen from The Galapagos Finches. The student has selected a comparison between seasons (first panel), and has selected "individual differences" as the comparison type (second panel). The particular constructed query is assembled at the bottom of the screen.

Strategic tools

Scaffolded tools can help represent more of the structure of the task for learners. We have designed the structure of *The Galapagos Finches* software as a strategic tool (Reiser et al., 2001; Tabak & Reiser, 1997; Tabak et al., 1996). The Galapagos Finches enables learners to investigate changes in populations of plants and animals in an ecosystem, and serves as a platform for learning principles of ecology and natural selection. The tool makes explicit the key strategies for examining ecosystem data — scientists can study a population through time (a longitudinal comparison) or split a population according to some dimension of interest, such as comparing male to female or young to adult (a cross-sectional comparison). These two families of comparisons are options students must select when constructing a query (shown as the choices "seasons" and "subgroups"). Similarly, students must articulate what type of comparison they wish to perform (looking at individual differences, relationship between two variables, and so on). In this way, students are led to articulate the strategic intent of a data comparison, rather than phrasing their action in terms of the surface details (see Figure 1). Similarly, in the ExplanationConstructor, disciplinary frameworks are represented in explanation guides that students use to ensure that their explanations address the key features of the framework (see Figure 2).
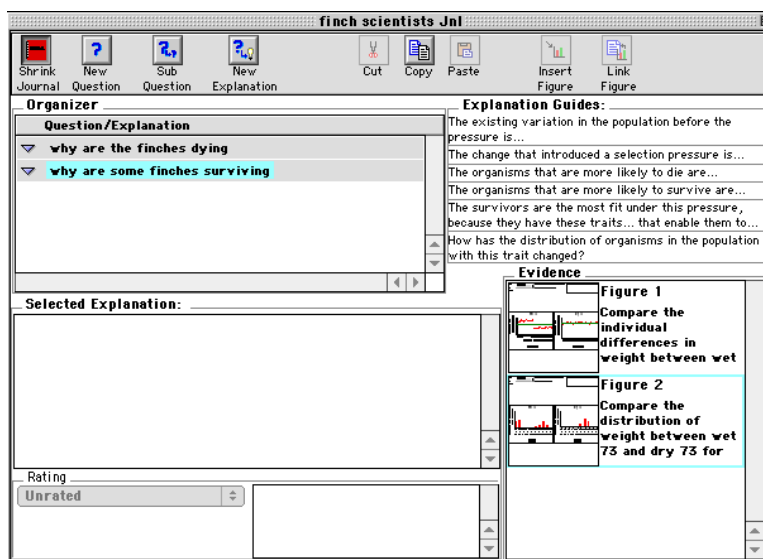
Figure 2. The ExplanationConstructor used to articulate questions, explanations, and backing support. The outline of questions, subquestions, and explanations is shown in the upper left Organizer panel. Explanation guides are shown in the upper right.

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

> Evan: *(reading prompt)* "Environment causes…"
>
> Janie: No!
>
> Evan: Yeah, "to be selected for…"
>
> Janie: Yeah, but that means like…
>
> Evan: // what food they eat //
>
> Janie: … organism with these trait
>
> Evan: // the trait being the food
>
> Franny: Yeah, that's right.
>
> Janie: No, because like, if my trait is to eat steak, and there's no steak, I'm immediately gonna go to something else.
>
> Evan: If you're only a vegetarian and you only eat… you don't eat meat, you're not gonna eat meat. Well, that depends…//
>
> Janie: Are you insane!?
>
> Franny: OK, OK. Don't think of people. Think of these guys (the finches). If they only eat one type of seed with their beaks and that seed is gone then they can't live anymore.

This example demonstrates the type of discourse we aim to create through the scaffolds. The structure they impose on students' work causes them to grapple with key disciplinary ideas such as the nature of a trait and the difference between a species' characteristic traits and learned behaviors. Decisions about the use of the artifact became the context for negotiation between the students of these important disciplinary ideas. Both sense making (interpreting the observed differences in individuals as candidates for traits supporting differential survival) and articulation were supported by the problematizing nature of the strategic tool.

Strategic artifacts

Just as the tools students use are structured to help them understand the task, we also structure the key work products students create to clearly represent important conceptual distinctions and task structure. Just as transparency in cognitive

artifacts that people use can affect the ease with which they can achieve their desired ends in actions in the interface, here we aim for transparency in the artifacts people create. Our goal is for students to create artifacts that clearly represent the important strategic and disciplinary thinking they have performed in creating the artifact. Contrast this with more traditional artifacts such as verbal essays, in which the research behind the essay and the deeper argument structure embedded in the essay may be very difficult to discern.

In the Animal Landlord, students study examples of animal behavior to isolate and analyze the key components of complex animal behavior (Smith & Reiser, 1998). Students study examples of behavior sequences such as hunting or eating and deconstruct the complex sequence into what they see as the important causal events. For each event, students record their observation of the event and their inference of the importance of that event (see Figure 3).

Figure 3. Strategic Artifacts from the Animal Landlord. Students decompose complex behavior into its constituents, categorize each constituent, and record their observations and interpretations.

The artifacts students create are structured to represent key aspects of the task. Students study complex behavior by decomposing a sequence into its constituents, represented by the rows of actions, and categorize each constituent, indicated in the label attached to the frame. Their analyses are structured into Observations (what we can see in the data) and Interpretations (what we infer from these observations) a key distinction in the scientific practice students are learning.

Again this provides both structure and problematizing. The structure prompts students to perform the subtasks of observation an interpretation. In addition, forcing them to categorize their observations pushes students to articulate their understanding and represent it in the artifact. The explicit distinction between observation and interpretation facilitates discussions geared at understanding the relationship between the two.

The following episode illustrates how the structure of the artifacts forces students to grapple with disciplinary content (Golan, Kyza, Reiser, & Edelson, 2001). This debate was recorded from a group of three 7th grade students who were watching a clip featuring two Golden Lion Tamarin monkeys eating a grape. One of the monkeys (the female) had the grape first and then the male took it away from her, jumped over her and moved to another branch. The students were arguing about the part in which the male Tamarin jumped over the female. Two of the students believed that was an instantiation of the "mount" behavior, while the third student did not agree. In essence this argument was about what "mount" means, is it merely contact between two animals or more than that?

> S2: What did we observe as mount? (reading)
>
> S1: No, that one is yours because I totally disagree with you guys!
>
> S2: Good for you! Come on man, you see in the clip it just looks mounting, they got on top of each other.
>
> S1: No, he jumped *over* her.
>
> S3: She, she jumped over him…
>
> S1: Whatever, she jumped over him.

S2: I know, but still, the contact…

S1: She jumped over him, doesn't matter, contact is not what you guys are talking about. Shoot, you are talking about like getting on top of each other and staying on top for a couple of minutes.

S3: No, no, no. We are not talking about that!

S2: No, no, not that, no, no, that's not. See, look, watch this contact. Boom! Look at that!

S1: Jumping *over*! *Over!*

This argument was finally settled by one of the researchers explaining to the students what the behavior "mount" means in the domain of animal behavior. This discussion surfaced students' implicit definitions of the behavior, an important step in learning to apply a categorization scheme. Again making these decisions as part of their analysis, and clearly representing these distinctions in the artifacts they create provoked these and similar arguments, surfacing disagreements and eventually refining students' definitions of these behaviors.

It is interesting that this disagreement had been brewing for some time in the group, but it had not been addressed. Had the group merely been asked to report a summary of their observations, it is possible this discussion would not have occurred. Forcing students to articulate their understanding and represent it explicitly using menu item labels and the Observation and Interpretation structure finally surfaced the differences in interpretation and provoked these productive discussions.

CONCLUSIONS

I have argued that scaffolding may occur through two complementary mechanisms, structuring and problematizing. Most accounts of scaffolding define support that helps students proceed through tasks. However, given the importance of connecting students' problem solving work to disciplinary content, skills, and strategies, it may also be important to provoke issues in students, veering them off the course of non-reflective work, and forcing them to confront key disciplinary ideas in their solutions to problems. The artifacts students use and create can be designed to map onto important disciplinary ideas and strategies, thereby problematizing these ideas as students use the tool to work through the task and represent the products of their work.

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