Designing Knowledge Representations for Learning Epistemic Practices of Science

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INTRODUCTION

Off and on for decades inquiry has been promoted as a means for engaging science students in scientific activity that promotes deep conceptual learning and develops students' scientific literacy. Most recently, national standards call for students to engage in inquiry as a means of learning what the scientific enterprise is all about (NRC, 1996). For the most part, although there has been a fair amount of research to document students' beliefs about the nature of science (Carey, Evans, Honda, Jay, & Unger, 1989; Carey & Smith, 1993; Lederman, 1992; Linn & Songer, 1993), relatively little attention has been paid to how we can support changes in students' scientific epistemologies (cf. Smith, Maclin, Houghton, & Hennessey, 1999). On theoretical grounds, the argument for engaging students in inquiry centers on the idea that the "final form science" (Duschl, 1990) of typical instruction develops a belief about science and scientific practice that is at odds with current philosophies of science (Hodson, 1988). There is also some evidence that students who see science as a dynamic enterprise of theory development are better able to integrate formal scientific conceptions with their everyday experience (Songer & Linn, 1991).

Knowledge representations can be instructional tools that focus students' conceptual and epistemological thinking in particular ways. For science education it is especially important that students learn to develop models and explanations of natural phenomena (Coleman, 1998; Coleman, Brown, & Rivkin, 1997), as well as learn how scientific theories and arguments relate to real-world phenomena (Driver, Leach, Millar, & Scott, 1996; Kuhn, 1993). Currently, various software tools support students' construction of models (Jackson, Stratford, Krajcik, & Soloway, 1994), explanations (Sandoval & Reiser, 1997), and arguments (Linn, Bell, & Hsi, 1998; Suthers, Toth, & Weiner, 1997) for natural phenomena. We are concerned with exploring how to support students' inquiry to foster an epistemological approach towards science learning as "science in the making" rather than as "ready made science" (Latour, 1987). Different knowledge representations can support students in important aspects of their inquiry including knowledge articulation, testing, communication, and refinement. Structured representations support students' participation in particular "epistemic games" (Collins & Ferguson, 1993): organized practices for representing and using forms of knowledge. We envision such knowledge representations as including models, argument maps, explanations, diagrams, simulations, and data (e.g., graphs, tables). Such knowledge representations can be coordinated and used to support productive collaboration between students for conceptual or epistemic change (Linn et al., 1998; Sandoval, 1998; Suthers, 1999; Vahey, Enyedy, & Gifford, in press).

This paper presents initial findings from our collaborative effort to understand the roles various kinds of scientific representations play in supporting students' epistemological learning in science, through their development of epistemic practices. We present concrete design principles for the development of representational tools that support students' inquiry and their development of scientific epistemic practices; and we sketch a framework for using such tools to support students' collaborative inquiry, both face-to-face and online. These principles elucidate what we have learned about the ways in which representational tools support students' articulation of their knowledge, evaluation and negotiation of those ideas with their peers, collaboration around the knowledge representations, and instructional practices that support such complex forms of inquiry. We first present a general overview of our meaning of epistemic practices and general design principles to promote them. Subsequent sections briefly describe how our various research efforts instantiate these design principles within knowledge representations and activities designed to guide students' use of these representations.

EPISTEMIC PRACTICES IN SCIENCE

We draw a distinction here between epistemic understanding and epistemic practice. Epistemic understanding refers to the set of ideas that we would like students to understand and be able to appropriate as they engage in or think about science. Epistemic practices are the cognitive and discursive activities that we want students to engage in to develop their epistemic understanding. To support particular practices, we have developed design principles for knowledge representations and activities in which such representations are used. Table 1 provides a general outline of the epistemic understanding we want students to develop, the epistemic practices that develop and in an important sense constitute that understanding, and design principles we have used to support these epistemic practices. The rest of this section describes these goals for epistemic understanding and the epistemic practices. Subsequent sections illustrate how our various design projects articulate the general design principles in Table 1.

Table 1:
Epistemic understanding goals, epistemic practices, and design principles for supporting them.

Goals for epistemic understanding
Seeing knowledge as an object of inquiry
Understanding various forms of scientific knowledge
Understanding criteria for evaluation of knowledge claims
Understanding the reciprocal nature of theory and data
Understanding representations within interpretive frameworks
Epistemic practices
Explicit articulation and evaluation of one's knowledge
Coordinate theory and evidence
Make sense of patterns of data
Develop representational fluency
Hold claims accountable to evidence and criteria
Design principles
Provide epistemic forms for students' expression of their thinking
Give distinct forms of knowledge distinct representations
Design representations that can be coordinated and linked
Representations should prompt and support epistemic (not just conceptual) practices
Communicate evaluation criteria and connect them to representations

Goals for epistemic understanding

Students' beliefs about the nature of science have been well studied, and generally students see science as the discovery of facts about the world rather than a process of constructing theories to try to explain the world (Carey et al., 1989; Driver et al., 1996; Lederman, 1992; Linn & Songer, 1993). We suggest that there are (at least) five major goals for students' epistemic understanding, and that if students can develop this understanding they will more effectively engage in self-directed inquiry, and develop deeper conceptual understanding of specific disciplines grounded within epistemological frameworks.

Knowledge as an object of inquiry

Epistemology is the branch of philosophy concerned with the origins, nature, methods, and limits of human knowledge. Clearly, to develop a personal epistemology about science students must be able to consider knowledge, their own and others, as an object of inquiry, or as D. Kuhn (1993) put it, an "object of cognition." Students' must be able to explicitly reflect upon what they know, how they know it, and why they believe it. Furthermore, students should develop views of science that recognize that scientific knowledge is socially constructed, including theoretical ideas, methods for investigation questions, and the criteria by which knowledge claims are evaluated.

Understanding forms of scientific knowledge

Scientific knowledge is represented in many different forms that differ in explanatory or predictive power, and that carry certain epistemological commitments. Moreover, various forms of knowledge are used to represent and explain different kinds of things. Theories, for example, offer broad explanatory (and sometimes predictive) power, and generate explanations for particular events. Models are usually explicit representations, often mathematical, of phenomena that are constructed from within theoretical perspectives. Scientific models attempt to generally attempt to characterize important relations among theoretical entities, but verisimilitude is not a requirement (e.g., chemists do not suggest that molecules are really balls connected by sticks, but ball-and-stick models convey important relationships about molecules). Within any given discipline, students need to understand the various forms of knowledge that are valued, and what are the agreed-upon uses for various kinds of knowledge and the methods for generating and evaluating new knowledge.

Criteria for evaluation

For students to become active participants in the construction of scientific knowledge, even just for themselves, they need to know the criteria by which scientific knowledge is evaluated. Such criteria include plausible causal mechanisms, parsimony, consistency with observed data, and consistency with current theories. New theories often are held to a criterion that they contain more explanatory power than existing theories (T. Kuhn, 1970).

The reciprocal nature of theory and data

Expert scientists and philosophers of science recognize that theoretical views influence interpretations of data, and even judgments about what counts as data within a discipline. Conversely, new data can sometimes lead to radical shifts in theoretical perspectives. Theory and data are thus reciprocally related, and it is an over-simplification to think of scientific activity as either theory-driven or data-driven.

Understanding representations within interpretive frameworks

Representations do not in and of themselves entail complete interpretive frameworks. Rather, models, diagrams, formulas, and other knowledge representations reflect choices about what is deemed assumed, and therefore implicit, and what must be explicitly represented. To use and create scientific representations successfully requires an understanding of the interpretive frameworks in which representations exist.

Epistemic practices

The above goals lead to a set of practices for generating and evaluating knowledge, a set of practices that we can meaningfully engage students in during science instruction. We suggest that the following practices, while not the only valuable epistemic practices we might want students to learn, are key practices for developing the epistemological understanding just described.

Explicit articulation and evaluation of one's knowledge

Given that we want students to see knowledge as an object of inquiry and to understand different forms of scientific knowledge, then their science learning should be centered around creating and evaluating knowledge. The argument for knowledge articulation and evaluation is common in current theories of learning. We want to emphasize that this practice is useful for more than deepening students' understanding of science concepts, but is crucial to students' development of sophisticated epistemological conceptions about science.

Coordinating theory and evidence

The central aim of science is to construct theories that explain natural phenomena. This effort requires the coordination of theoretical ideas with the data that provide evidence of their utility as explanations. A key aspect to the practice of coordinating theory and evidence is to be able to distinguish claims from evidence. The practice of coordinating theory and evidence entails using theories to explain data, and using data to evaluate theories. This could be done a number of ways, as demonstrated by the approaches described in the following sections of this paper.

Making sense of patterns of data

An important aspect of theory building is the development of explanatory frameworks that make sense of disparate sources of data, by imposing patterns on them. Scientists often speaking of seeing patterns in the data, but the patterns that we see are constrained by our own theoretical frameworks. For students, the desired practice of making sense of patterns of data includes the explicit consideration of multiple sources of data. Also, in combination with the practice of coordinating theory and evidence, looking at the same data from alternative perspectives is an important way to make sense of them.

Develop representational fluency

We view *representational fluency* as being able to interpret and construct various disciplinary representations, and to be able to move between representations appropriately. This includes knowing what particular representations are able to illustrate or explain, and to be able to use representations as justifications for other claims. This also includes an ability to link multiple representations in meaningful ways.

Hold claims accountable

Understanding the criteria to which scientific claims are held, and the essentially social nature of science, requires that students' own knowledge claims be accountable to these criteria. We view discourse as a central means to realizing this practice in classrooms. Science classrooms should be organized as knowledge building communities (Scardamalia & Bereiter, 1993) in which discussion and debates about claims and evidence are central activities. Students should be encouraged to justify their claims, and causal claims should be challenged with respect to available data and consistency with other theories and knowledge.

Design principles for epistemic representations

Our collaborative analysis of our various efforts to support students' inquiry into science and mathematics has identified two broad kinds of representations that support epistemic practices. One type of representation are explicitly epistemic representations, especially structures for students' representation of arguments. Such representations are designed to reify epistemological commitments and directly support epistemic practices. It may or may not be the case that such representations correspond to representations or inscriptions common to scientific practice. The second type of representation includes discipline-specific models, such as molecular models in chemistry or the representation of outcome spaces in probability. Such representations are common to expert practice in the discipline, and as such their epistemic features are often implicit.

The following sections describe our approaches to designing such representations, with an emphasis on the particular design principles each representation instantiates, and the epistemic practices each representation supports. It is beyond the scope of this paper to present detailed empirical findings about how these representations function in various learning settings. Where possible, we have included references to more detailed explication of our several studies.

EXPLANATIONCONSTRUCTOR: REPRESENTATIONS AND ACTIVITIES FOR SCIENTIFIC EXPLANATION

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ExplanationConstructor is a software tool designed to support students' explanation of problems of natural selection and evolution, as part of technology-infused curricula developed as part of the BGuILE project (Reiser et al., to appear). Following research showing that when students understand the purpose of experimentation as the discovery of causal relationships they are better able to design and conduct experiments (e.g., Dunbar, 1993; Schauble, Glaser, Duschl, Schulze, & John, 1995), a basic premise of our approach has been to focus students' inquiry in terms of the products that inquiry should produce. Our focus has been on students' development of causal, evidence-based explanations. Our general approach is described in detail in Reiser, et al.

The discussion here is confined to a description of the design principles used to develop representations in ExplanationConstructor of important epistemic entities students work with during inquiry. This section briefly highlights how we have explored a set of trade-offs among how various knowledge representations support or hinder students' epistemic practices, and how other materials and activity can support students' interaction with these representations. This section summarizes the design history of ExplanationConstructor, and how classroom studies of its use have led to its development. The primary point we wish to make here is that knowledge representations such as those discussed in this paper, and others, support certain aspects of students' reasoning about the nature of scientific knowledge, as they create it, but that in themselves such representations are insufficient to push students to explicitly consider their own epistemological commitments or the implicit epistemological commitments underlying scientific inquiry.

Grounding epistemic forms in specific domains

ExplanationConstructor was specifically developed to structure students' efforts to construct scientific explanations. The issue was to figure out what kind of epistemic forms would scaffold students' learning to play the "scientific explanation game." There were two epistemological standards for scientific explanations that we wanted students to be able to satisfy: 1) the articulation of clear, coherent causal explanations for natural phenomena that 2) were supported by appropriate evidence. Our guiding design principle was that an epistemic form that represented these two criteria should be grounded within the domain of students' inquiry, in this case the domain of evolution and natural selection. Another principle was that students' explanations be tied to their efforts to answer specific questions, and that explanations be represented distinctly from the data used as evidence to support them (see SenseMaker and Belvedere, below).

Link explanations to specific questions

The first version of ExplanationConstructor, illustrated in Figure 1, has been described in detail elsewhere (Sandoval, 1998; Sandoval & Reiser, 1997). In relation to our goals for students epistemological understanding, it was important to communicate not only what scientific explanations are like, but what they are for. Our stance was (and is) that explanations answer specific questions, so explanations should be linked to specific student questions. In ExplanationConstructor, students first recorded a question they were trying to answer, then later created one or more candidate explanations for it (see Sandoval, 1998 for details about the BGuILE curricula and how students worked through specific investigations). Linking questions and explanations seems to have helped students monitor their progress in terms of what they felt they needed to know, their questions, and what they felt they did know, their explanations. Because these representations are distinct and persistent, students could return them over the course of their extended investigations of problems of natural selection. Moreover, group monitoring was focused in epistemic terms, concerning the ability of explanations to answer questions (Sandoval, 1998).

Represent theories as explanatory frameworks

One feature that distinguishes ExplanationConstructor from other collaborative inquiry tools, such as Belvedere, described below, or CSILE (Scardamalia & Bereiter, 1993) is that it provides domain-specific scaffolds through *explanation guides* (we have earlier called these explanation templates, Sandoval & Reiser, 1997). Explanation guides provide both conceptual and epistemic scaffolds. Conceptually, explanation guides focus students on the appropriate content of specific explanations. In Figure 1, for example, the "selective pressure" guide visually represents the theory of natural selection into components that prompt students for the important constituents of a natural selection explanation.

Epistemically, explanation guides encourage students' to think about theories as explanatory frameworks, super-ordinate to explanations for specific events. For each problem that students investigate, there are multiple guides to choose from. Because students have to choose explanation guides for each explanation, they are encouraged to map their emerging understanding into domain theory, to place themselves within a particular explanatory framework.

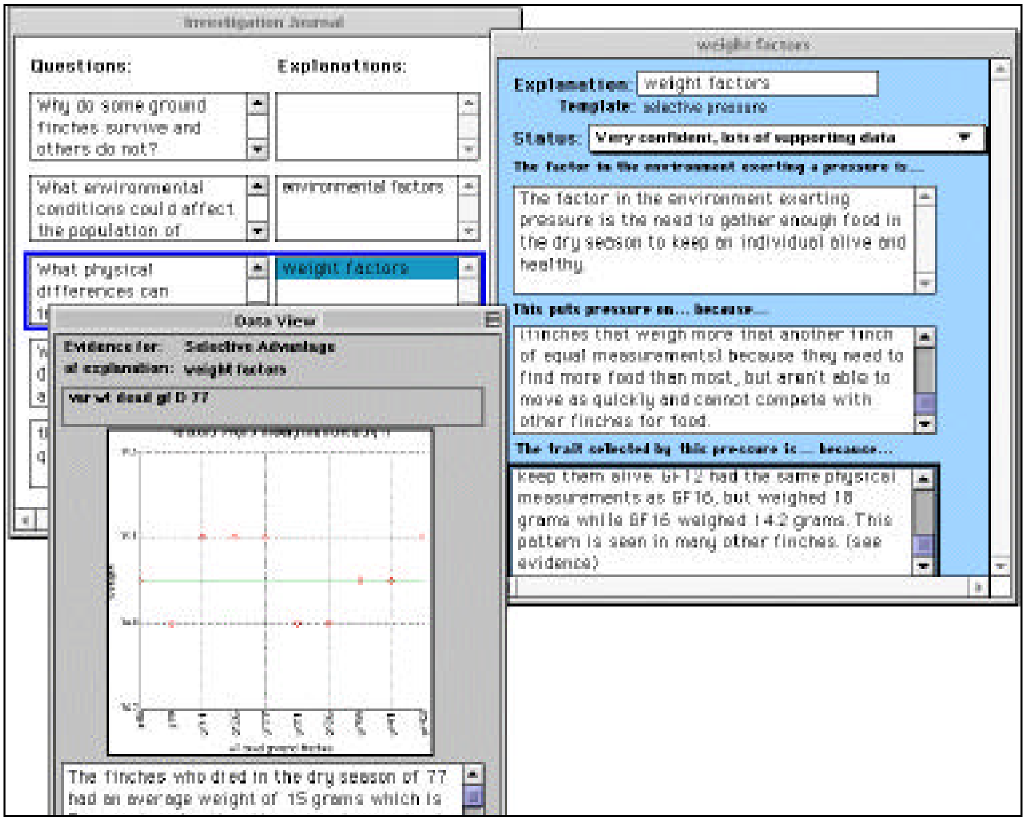

Figure 1:ExplanationConstructor 1.0. Questions, explanations, and evidence are distinctly represented, and explanations are highly structured (right).

Classroom studies of this first version of ExplanationConstructor showed that templates often provided direct guidance for students about their progress and about what data they should look for next (Sandoval, 1998). That is, groups could see how much of an explanation they had completed, and the specific prompts within guides suggested the kind of data that could help them complete each component. Of course, such guidance was available only prospectively, when students created new explanations before looking at all the potentially relevant data.

Linking evidence to causal claims

Data are not in themselves particular epistemic forms, but they have quite a different epistemological status from the causal claims derived from them. This distinction, as noted earlier, is often not made by students, but they seem to view explanations as being embodied in data, not interpretations given to data. ExplanationConstructor not only represents the data that students use as evidence separately from their causal claims about that data (Figure 2). Students have to actually select specific pieces of data as evidence, and then link them to specific causal claims. Thus, the theory-evidence distinction is made both in the representations students use and in their manipulations of those representations.

This first version of ExplanationConstructor seemed to provide productive supports for epistemic practices during students' small-group collaborative inquiry. Students engaged in frequent monitoring of their progress in explicitly epistemic terms, especially in evaluating the quality of their explanations as answers to their questions and whether or not they were based on appropriate data. Students' investigations were also highly planful, consistently focused on satisfying explanatory goals over the course of sustained, week-long investigations. On the other hand, the work-sheet like representation of the explanation guides sometimes worked against students' articulation of coherent explanations.. Also, the facility for linking and later viewing evidence was a bit opaque, consequently students rarely cited data for their explanations even though it was clear that they had examined relevant data and were reasoning from it.

Material and activity supports for evaluation

These findings motivated revisions to the ExplanationConstructor tool and spurred us to design other material supports that would encourage students to consider the quality of their explanations more explicitly, such as whether or not they were coherent and how specific causal claims explained specific data.

Clarifying connections between epistemic entities

A significant change to ExplanationConstructor was to make more clear the relationship between the different epistemic entities represented within the tool, namely questions, explanations, and evidence. One change was to organize questions and explanations hierarchically, to make it more clear that explanations answer particular questions. The hierarchy also allows students to explicitly record sub-questions subordinate to the over-arching questions of their investigations. For example, as shown in Figure 2, when trying to answer how the bacteria that cause tuberculosis can survive antibiotics, it might first be necessary to determine how antibiotics attack cells as a step in identifying potential differences between bacterial strains.

Another change was to make students' selected evidence for their explanations much more visible and salient (Figure 2). We also changed the way students cited data to allow them to insert a reference to data anywhere in their explanations and encouraged them to include them immediately after relevant causal claims. We found in a subsequent classroom study that not only did students cite more data in their explanations, but that they often explicitly discussed why that data was important evidence (Sandoval, 1998).

Another change to the software was to move the explanation guides out of the space where students wrote their explanations. Thus, they were still available for guidance, but students became more responsible for supplying connective causal language in their explanations. in fact, this is what seemed to happen. We do not yet know, although analyses are underway, whether or not these slightly removed explanation guides continued to productively direct students' investigative activities as the previous version had.

Explanation evaluation as a social practice

As far as students' epistemic practices are concerned, probably the single most important revision we made was to develop a specific rubric for students' evaluation of their explanations, and to provide them with clear opportunities to apply the rubric. This rubric highlights what we consider to be four key epistemological criteria for scientific explanations: 1) that they articulate a clear, coherent chain of cause and effect; 2) that they are supported by sufficient relevant evidence; 3) that alternative explanations of data have been explicitly considered and ruled out; and 4) that students articulate the limits of their own explanations, even those they consider their best ones. This rubric, although designed by participating teachers and the research group, becomes an object of discussion between students and teachers, and students take ownership of the criteria through their evaluation of their own and their peers' work.

ExplanationConstructor has a review facility that students can use to assess themselves or their peers. These reviews are tied to specific explanations (Figure 2), and are given using the rubric. Fundamentally, though, explanation evaluation is a social process, governed by the socioscientific norms (Tabak, 1999) of specific classrooms. An important goal of inquiry-based science learning ought to be to help students appropriate those norms, and to understand the epistemological commitments that underlie them. Consequently, a central feature of BGuILE curricula are mid-investigation peer reviews, and post-investigation consensus-building discussions. Mid-investigation reviews give students the chance to be reflective critics of each other's work, while maintaining an opportunity to respond to specific criticisms. They also give students repeated opportunities to apply the criteria of the explanation rubric. Post-investigation class discussions publicly articulate students' findings and allow students' to evaluating competing ideas to develop a consensus explanation for each problem. Throughout the unit, these consensual discussions provide teachers with opportunities to tie specific investigative experiences to broader domain principles.

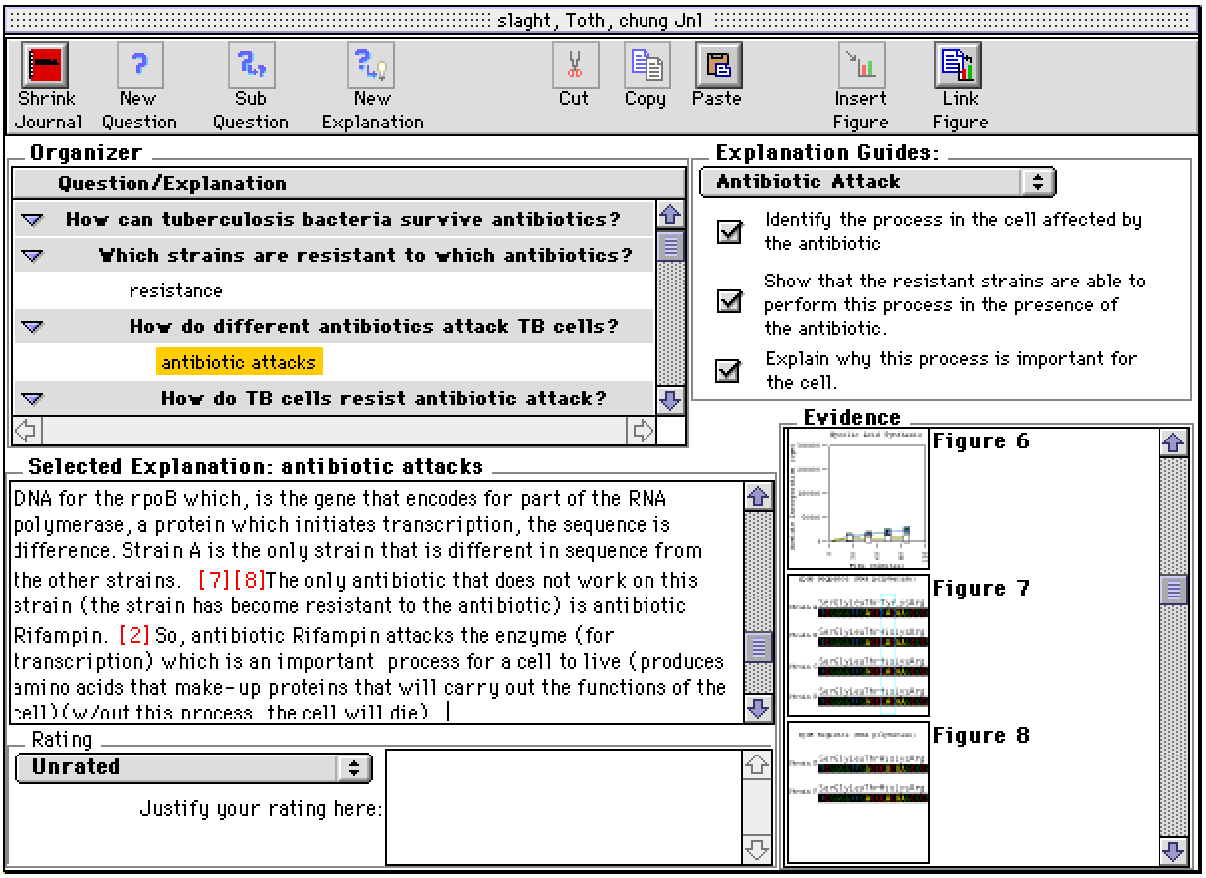

Figure 2: ExplanationConstructor 2.0, showing the relations between questions, explanations, and evidence.

We found that students' critiques of each other noted a lack of specificity, especially failures to state causal mechanisms, as well as a lack of data as evidence. Students' most common self-assessments of their explanations at the end of an investigation were to acknowledge the limits of their accounts. Thus, the rubric and activities combined to encourage students to reflect on the quality of their own and each others' explanations in epistemologically important ways, and in a way that merely the construction of those explanations did not encourage.

SENSEMAKER: REPRESENTING ARGUMENT-EVIDENCE RELATIONS FOR CONTROVERSY-FOCUSED SCIENCE EDUCATION PROJECTS

Philip Bell, University of Washington

SenseMaker is a knowledge representation software tool and instructional approach that reifies and supports aspects of scientific argumentation for educational purposes (Bell, 1998; Bell & Linn, in press). It uses *argument maps* as a representational scheme to highlight the coordination of theory and evidence for the purpose making individual and group thinking visible. SenseMaker has been used predominantly for classroom science projects where students are exploring a controversial topic in science (Bell, 1998). More recently, we have been exploring the use of SenseMaker as the knowledge representation component of on-line communities focused on knowledge networking.[1]

Design Principles for Using a Knowledge Representation to Support Argumentation

In the rest of this section, I describe four design principles derived from research on the instructional use of SenseMaker as part of the project-based approaches used in the KIE (Bell, Davis, & Linn, 1995), SCOPE and WISE research efforts. The principles were identified and refined through iterative cycles of design, enactment, and study (Brown, 1992; diSessa, 1991).

There is increasing empirical support for the notion that educational innovations—whether they make use of technology or not—are systemic or package-like in their nature (Brown & Campione, 1998; Salomon, 1996). For this reason, I have made connections between the following subset of principles as I describe them. These principles, of course, also connect to designed and emergent aspects of the educational package and setting that extend beyond the scope of this section. For this reason, the four principles that follow should only be considered a partial depiction of this particular effort. Specifically, the following four design principles focus on the central use of SenseMaker argument maps as a knowledge representation scheme for controversial topics.

Theory-Evidence Coordination. Left to their own accord, middle school students rarely incorporate instances of evidence into their arguments about science. Argument

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[1] We are exploring this use of SenseMaker as part of the SCOPE project (see http://scope.educ.washington.edu/).

representations should promote theory and evidence presence, distinction and coordination.

This principle is motivated by the image of science represented in the epistemic goal that students "understand the reciprocal relationship between theory and data." The epistemic game of interest here focuses on a coordination of evidence—our version of data to be interpreted—and theoretical claims associated with the topic of inquiry. Researchers have documented how students do not come to science class understanding this type of argumentation (Driver et al., 1996; Kuhn, 1991).

Based on this prior research, is it unreasonable to expect students to productively coordinate evidence and theory? That is, do students have an epistemological facility for engaging in such evidence-theory coordination if they were to receive appropriate supports and enculturation? Prior research on the use of SenseMaker has documented how students can regularly coordinate evidence and theory when provided with appropriate supports (Bell, 1998; Bell & Linn, in press). Both *evidence* and *theoretical claims* are components of the ontology associated with the SenseMaker software—as dots and frames, respectively. Figure 3 shows a fragment of a SenseMaker argument representation.

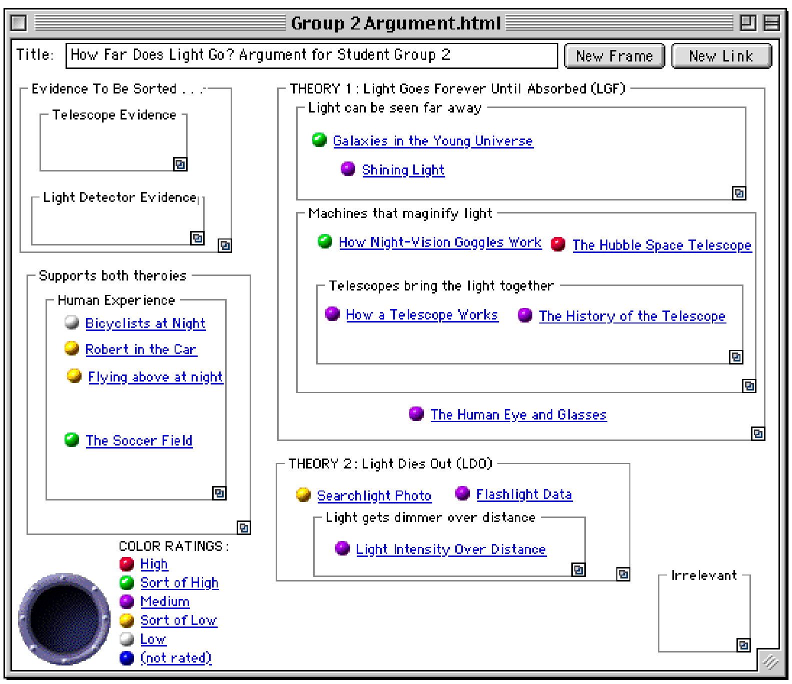

Figure 3: Student Argument Map in SenseMaker showing evidence dots and nested claim frames

The active coordination of evidence and theory in the representation also supports the epistemic goals of *knowledge being the object of inquiry* in science and the importance of *understanding the reciprocal relationship between theory and data*. This creation and tethering of evidence and theory is the inquiry students are engaged in during our controversy-focused debate projects. Through this particular depiction of scientific argumentation (which is an intermediate form to be sure) students are being introduced to an important form of scientific knowledge—another of our goals for epistemic understanding.

<u>Evidence Collections</u>. When students do attend to evidence in their argumentation, they tend to fixate on individual pieces. Argument representations should promote students' engagement with a collection of evidence.

Research has shown that students tend to predominantly focus on single instances of evidence (when they attend to it at all) to inform their claims and arguments (see Driver et al., 1996 for discussion). Elaborating upon the epistemic priority we've given to THEORY-EVIDENCE COORDINATION, we have found that students benefit from being encouraged to consider a collection of evidence as they engage in argumentation (Bell, 1998). By exploring an evidence collection and being asked to represent and coordinate the set in the argument representation, students are encouraged to not fixate on individual pieces. Making sense of an evidence collection is a unique affordance of the SenseMaker representation. It supports the epistemic practices associated with *having students make sense of patterns of data* as they *coordinate theory and evidence*.

<u>Shared Corpus of Evidence</u>. Engaging classes of students with a common corpus of evidence will allow the teacher to more quickly refine usable pedagogical content knowledge and instructional strategies related to the topic. It will also help establish an increased degree of common ground during classroom discussions.

As important as it is to represent a COLLECTION OF EVIDENCE in an argument representation, we have found it useful for that collection to consist of a shared corpus for students to explore as part of the curriculum project. An alternative would be to allow pairs of students to explore different collections of evidence. It is likely that this alternative approach could be used to promote the development of distributed expertise within the classroom (Brown & Campione, 1998). But, what are the possible benefits of using a shared evidence corpus for all students in a class?

First of all, a shared corpus allows the classroom teacher to develop pedagogical content knowledge relevant to supporting students with their engagement with the evidence and thinking about the project topic (Wilson, Shulman, & Richert, 1990). Predictably, each piece of evidence cues prior knowledge somewhat systematically from the students. Pieces of evidence of different forms also benefit from particular types of engagement with understanding that piece. For example, an evidence item that depicts a specific laboratory experiment calls for an interpretation of details from the experiment and the associated data generated.

Another important consequence associated with using a common corpus of evidence is that it helps establish common ground in the discourse of these learning communities as they explore the project topic (Edwards & Mercer, 1987). The corpus allows groups of students along with the teacher to work toward a shared understanding of the same phenomena and theoretical ideas. In a related manner, students will often invoke common life experiences as a form of evidence in their verbal arguments in order to make their arguments more compelling and understandable. For this very reason, we also have students extend the SHARED CORPUS OF EVIDENCE with instances of this evidence from their own personal life experiences. It also allows students to connect the project topic to their own lives and develop more an integrated understanding of the topic.

Represent student thinking and topical perspectives. Promote the use of the argument representation as a blended representational medium that depicts: (a) students thinking and theorizing about the controversial topic (based on their prior and evolving understanding), and (b) different perspectives associated with the controversy.

…further refining the principled focus on EVIDENCE-THEORY COORDINATION through an engagement with an EVIDENCE COLLECTION that is SHARED, we can now describe how SenseMaker can serve as an inscriptional system for representing students' scientific ideas, notions, conjectures on the one hand and various perspectives (perhaps hypotheses, positions, solutions, or propositions) about the controversy topic associated with the project. Although both dimensions of this knowledge come to be represented, they become interrelated (or blended) in the actual representation. This is typically an interaction of how the representation was originally designed by the project developer (or teacher), and how the students represent their understanding and conjectures visibly in the representation.

As the project begins in the classroom, the SenseMaker representation is set-up with some initial theoretical structure built into it in the form of competing claim frames. In this regard, it is useful to map out the competing perspectives associated with the controversy. For example, in a debate project about whether or not DDT should be globally banned, positions that could be initially presented to students as they commence working would include different policy positions about banning DDT due to its severe impact on ecosystems and a position arguing for a moderated use of DDT since prevents multitudes of deaths each year from malaria in almost two dozen countries. The DDT ban topic is predominantly a policy issue. With a topic that is more of a strict scientific debate, the different perspectives initially represented might be the competing hypotheses being explored.

Apart from looking to the topic for guidance in the initial design of the representation, it has also been useful to represent positions that will resonate with students initial thinking about the topic—in order to give them a way to easily represent their personal understanding in their argument map. The blend of the student thinking within the perspectives associated with the topic can promote active sense-making and perspective-taking on the part of students (see Bell, 1998 for details).

Will students spontaneously theorize about the evidence and about the topic? The short answer is that it depends. If the topic is one associated with students' everyday experiences, they are more likely engage with the topic in a naïve realist manner. That is, they will have a natural tendency to be phenomenologically descriptive of evidence and take evidence as an unproblematic depiction of theoretical perspectives (cf. Driver et al., 1996). As students COORDINATE EVIDENCE AND THEORY, other aspects of the SenseMaker approach can support students in theorizing about evidence rather than being simply descriptive (for details see Bell, 1998; Bell & Linn, in press).

BELVEDERE: REPRESENTATIONAL GUIDANCE FOR REASONING ABOUT EVIDENCE

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From its conception, the Belvedere project has been concerned with the role of representations in fostering epistemic practices in science (Cavalli-Sforza, Weiner, & Lesgold, 1994). The initial goal was to provide a rich graphical notation for the full range scientific argumentation, along with a software coach that would help students express and refine their arguments. The original notation represented various forms of scientific propositions (such as data generalizations, hypotheses and theories) as nodes, and connected them with links representing various types of relationships, including evidential/explanatory (supports, predicts, explains), argumentive (warrants, undercuts), logical, causal, and temporal relations. We used graphical representations in order to provide students with concrete forms for the abstract components and relationships of theories and related arguments, and to enable both students and the automated coach to identify ways in which further contributions can be made to the argument.

Subsequently the project emphasis shifted to collaborative learning rather than one-on-one tutoring. Observations of pairs of students working with the argumentation representations (Suthers & Weiner, 1995) indicated that the representations as we designed them were too complex for students' initial encounters with this new and unfamiliar kind of activity. As a result we simplified the representations to focus on two fundamental distinctions: the epistemological distinction between empirical and theoretical propositions, and the evidential distinction between consistency and inconsistency relations between these propositions. Subsequent work included preparation of a classroom implementation methodology, along with "science challenge" problems and peer-assessment rubrics (Suthers et al., 1997).

In this section I reinterpret Belvedere's representations in terms of the epistemic goals, epistemic practices, and design principles described in the first section of this paper. In each example I will work from goals to design principles that address these goals, and then indicate how application of each given principle in Belvedere prompts students to engage in the desired practices. In a few cases I will note deficiencies in Belvedere's design and potential improvements. I will then consider the question of alternative representations, and describe ongoing work that seeks to uncover ways in which these alternatives may differ in their prompting of epistemic practices.

Goal: Seeing knowledge as an object of inquiry

The most fundamental epistemological goal is that learners see knowledge as an object of inquiry. Without this epistemological stance, the other goals discussed in this paper cannot be achieved.

Principle: Provide epistemic forms for students' expression of their thinking

The corresponding design principle is also fundamental: our software (and other educational media and activities) should provide visible representations that make knowledge explicit as objects to be constructed, manipulated, and evaluated through public negotiation. The other design principles are simply refinements on how this reification of knowledge should be accomplished.

Practice: active manipulation of representations of knowledge as object

Learners using Belvedere make the information that they are interpreting and the hypotheses that they are formulating and evaluating visible as shapes in a graph, and make the structural aspects of their evidential arguments visible as links (Figure 4). We hypothesize that the activity of creating and linking knowledge representations guides learners to view their knowledge as open to intentional manipulation, just as the representations are.

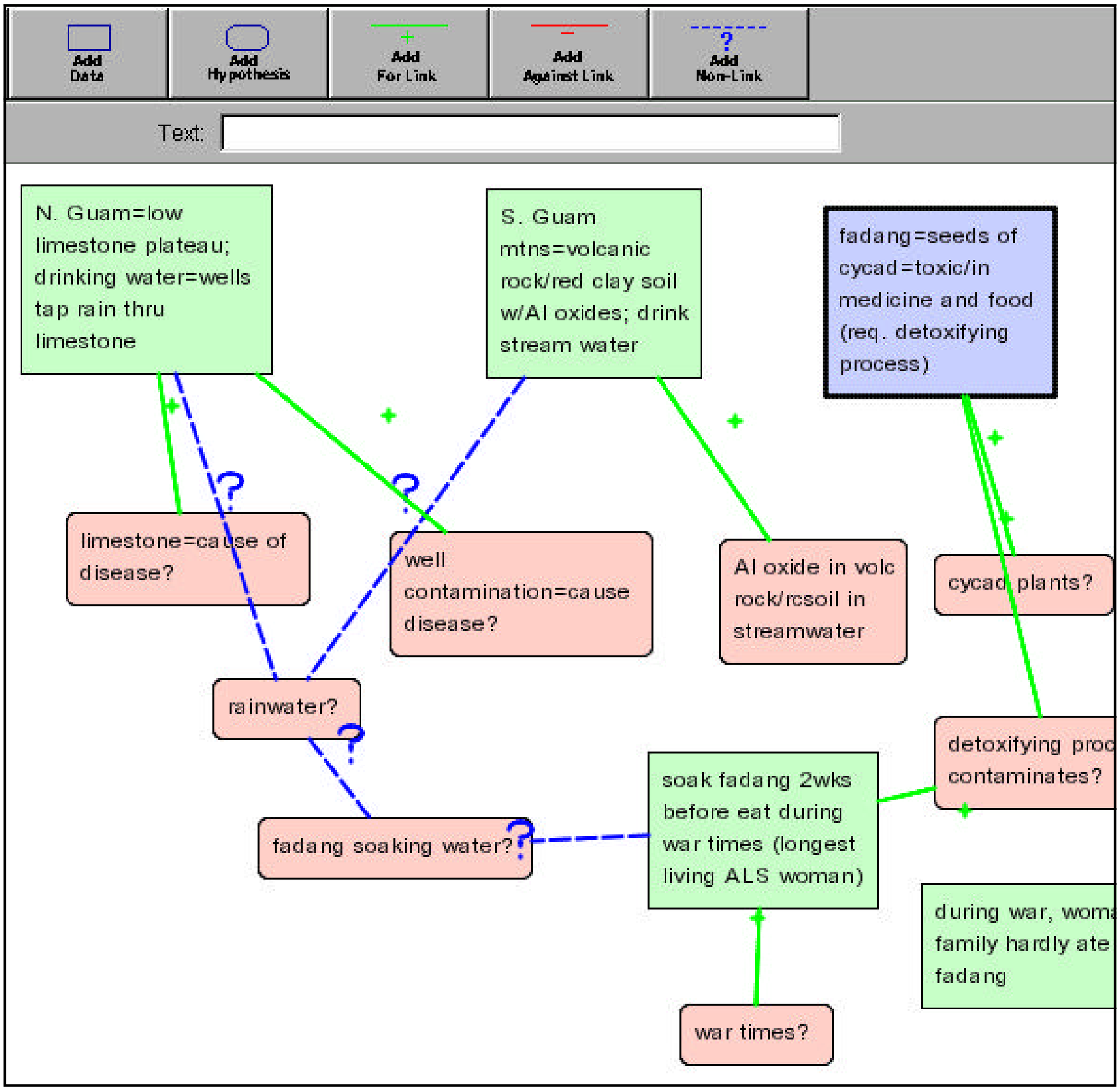


Figure 4. Evidence map under construction.

For example, consider the following transcript from a study with college students investigating possible causes of the disease ALS on Guam. The students have just generated three hypotheses concerning possible contaminants in water sources (the water is used to remove toxins from fadang, a food source). One student (L) proposes making an explicit record of their uncertainty, to be resolved later, using three links of type "unspecified" (the "?" links in Figure 4). This constitutes an example of use of the representations to reflect an explicit acknowledgement of the status of their knowledge and their intention to refine that knowledge.

L: There's so much difference with the water.

R: Rainwater, well water, stream water. <laughs>

L: Yeah! Maybe we can just put it so that we know, and maybe we can connect that hypothesis saying that what they soaked it in was the rainwater, so therefore the rainwater… you know? <Pointing from bottom left to top center of notes>

R: Oh, okay, it could be either or.

L: Yeah. So if it was stream water, we could connect it to there <Pointing to center of screen> So we know that in the stream water, like…

R: So we connect these two right here? <Pointing with cursor from H3 "rainwater?" to D4 "soak fadang 2wks…"> No? Make another one?

L: Yeah.

R: So make another hypothesis, or make another…

L: Fadang, soaking water. <Typing H8: "fadang soaking water?">

R: Oh, that's the hypothesis?

L: Yeah. So later if we find out what kind it is, we can connect it. <Pointing to center of notes> So that if it's stream water, then we'll know that inside the stream water they used, there was this.

Goal: Understanding various forms of scientific knowledge

Given that one is treating knowledge as an object of inquiry, other considerations come into play. Learners must first be able to discriminate different forms of knowledge before they can treat these forms according to their different status. "Epistemology" is concerned with the origins of knowledge. The most fundamental epistemological distinction to be appreciated by learners is that between empirical observations -- knowledge that comes from the world -- and theoretical claims -- knowledge that comes from our attempts to make sense of the world. Empirical observations have a primacy that theoretical claims ones do not; while theoretical claims have explanatory power that empirical ones do not. Hence we wish to design representations that scaffold awareness of these distinctions.

Principle: Give distinct forms of knowledge distinct representations

The consequent design principle, that distinct forms of knowledge should be given distinct representations, is adhered to in Belvedere by the use of different shapes (and the corresponding toolbar commands that create them) to represent "data" versus "hypotheses." Similarly, different kinds of links (and commands) represent "for" versus "against."

Practice: Learners practice identifying and speaking in terms of the forms.

If we have succeeded in our design, learners will be prompted by their use of the software to practice speaking in terms of these distinctions. This prompting is what we tried to accomplish when we focused Belvedere's representations on the two fundamental epistemological and evidential distinctions discussed previously, deferring for the time being elaboration into other nuances of scientific argumentation. The following dialogue excerpt (from one of our early middle-school studies) illustrates how the requirement, imposed by the software, that one make a choice along the epistemological dimensions of empirical versus theoretical can lead to peer coaching on the meaning of this distinction. (The software used the terms requested by the classroom teacher: "data" and "claim".)

> S1: So data, right? This would be data.
>
> S2: I think so.
>
> S1: Or a claim. I don't know if it would be claim or data.
>
> S2: Claim. They have no real hard evidence. Go ahead, claim. I mean who cares? who cares what they say? Claim.

Goal: Understanding the reciprocal nature of theory and data

The hallmark of a good theory is that theoretical claims are consistent with known empirical observations while also predicting interesting new ones. We wish to maximize the consistency between theory and observations (including predicted as well as confirmed observations), while minimizing inconsistencies. Theory and data are reciprocal in process as well as structure: good data often lead inductively or serendipitously to new theories; and good theories predict new observations to make.

Principle: Enable coordination and linking of representations of data and theory

Representations should prompt one to consider and seek out relationships between theory and data. This is the primary point of Belvedere's graphical representation, in which learners construct explicit links between different types of propositions. The graphical representations are also intended to make it easy to see patterns of relationships, particularly patterns that might prompt new constructive activity such as seeking further evidence bearing on a hypothesis that seems weakly related to the data at hand, or finding data that discriminate between two hypotheses that seem to explain the existing data equally well. These opportunities for constructive action are pointed out by a software advisor, which provides advice based on patterns in the evidence graphs (Paolucci, Suthers, & Weiner, 1996; Suthers, Weiner, Connelly, & Paolucci, 1995).

Practice: Learners see their task as actively relating theory and data

Empirical work with Belvedere provides ample evidence that Belvedere prompts learners to consider evidential relationships between propositions. A recent pilot study quantified the effect. Pairs of middle-school students worked on an open-ended science investigation. We measured the percentage of on-task verbal utterances that addressed issues of evidential relationships. Talk about evidence was an order of magnitude greater for two pairs of students using Belvedere (5.2%, or 32 of 613 on-task utterances) than for two pairs using a text editor (0.5%, 4/694).

Belvedere's representational guidance of reasoning between data and theory could be improved. The representations provide no guidance in considering the generation of new hypotheses from data or making empirical predictions from theory. These activities require domain-specific knowledge which Belvedere was not designed to capture.

Goal: Understanding criteria for evaluation of knowledge claims

Not all propositions are created equal. As propositions become part of the scientific knowledge-building discourse, we need to evaluate them against criteria such as reliability and objectivity of measurement instruments, coverage of the empirical observations by theories, and internal consistency of theories.

Principle: Enable annotation of knowledge claims with evaluation criteria

Our representations should make the criteria for evaluation, and preferably their application to knowledge claims, visible. This is a specialization of the principle of making knowledge building visible.

Practice: Hold claims accountable to evidence and criteria

Belvedere's representations provide for evaluation in two ways. First, the visible configurations of consistency and inconsistency links enable learners to quickly assess the relative support for and against hypotheses, including their coverage and the presence of conflicting evidence. Second, one can change the line thickness of all graphical knowledge representation objects to express the learners' confidence in them -- a feature not used much by students in our field studies, perhaps because the manipulation by which one adjusts strength was available only via a menu.

A limitation is that the criteria by which one makes evaluative judgements were not explicit in the representations, although they were offered in textual form by the automated advisor**.** The advisor highlights the knowledge objects of concern, states a general evaluative principle and states its implications for action in the present case. Belvedere's representations might do more work in guiding epistemic reasoning if the criteria themselves were made explicit, perhaps as patterns which learners could visually match to their graphs.

Ongoing work

Implicit in the foregoing discussion -- and in much of the work in this field -- is the assumption that we know how to design representations that make certain aspects of knowledge visible and guide learners' thinking and acting. Design decisions are often made based on designer's intuitions and informal work with users rather than being informed by explicit study of the question. As a result it is not surprising that software tools with goals similar to those of Belvedere (supporting epistemic practices among collaborative learners) utilize representations as diverse as graphs (e.g., Belvedere), threaded discussion (e.g., Web-Camile and Web-SMILE, Guzdial et al., 1997), linked notecards (e.g., Collaboratory Notebook, O'Neill & Gomez, 1994), containers (e.g., SenseMaker, Bell, 1997), or some combination thereof (e.g., CSILE, Hewitt & Scardamalia, 1996). There are both empirical and theoretical reasons to believe that the expressive constraints imposed by a representation and the information (or lack of information) that a representation makes salient may have important effects on students' discourse during collaborative learning (Suthers, 1999). However, to date no systematic study has been undertaken to explore possible effects of this variable on collaborative learning. I am currently conducting such a study, comparing three representational tools for recording evidential relationships: unconstrained text (control condition), Belvedere-style graphs, and matrix representations. The study is comparing both process measures (e.g., talk about evidence) and outcome measures (e.g., memory for problem facts and quality of argumentation in a written essay). The matrix representations are expected to lead to the most exhaustive consideration of evidential relations, perhaps at the cost of not focusing on the most important ones.

It is not the intent that alternate representations be viewed as mutually exclusive. In fact, we are currently implementing a new release of Belvedere that will enable one to switch at will between graph, matrix and tree (hierarchical list) views of one's emerging evidence model. Such a tool opens up new possibilities in the study of representational competencies, including coordinating the use of multiple representations as well as choosing a single representation that best matches the cognitive task at hand.

CHEMSENSE: DEVELOPING REPRESENTATIONAL FLUENCY IN CHEMISTRY

Elaine Coleman, SRI International

In chemistry, the use of representations is an inseparable part of the study of chemistry. Representations, whether they are in the form of models, symbols, diagrams, or graphs, help to tell a story or provide a framework to help students visualize the "world" of microscopic particles.

For high school students studying chemistry, as compared to other sciences, this may be their first organized encounter with a science that is, in many ways, very much removed from their everyday experience. Whereas biology and physics are often within the context of previous student experience, much of chemistry is untouchable and unobservable and therefore relies on a system of representations to explain chemical phenomenon (i.e., color change to represent that a chemical reaction occurred). Consequently we believe that students need to acquire a certain representational fluency or literacy when it comes to understanding chemistry.

We have been developing a learning environment called ChemSense which enables students to construct their own representations and animations or use a variety of ready made representations as they work with chemistry probes during lab experiments.

Prior to our design and development we needed to find out how well chemistry students used visual representations. We conducted a series of interviews designed to prompt students to explain chemical phenomena. This was a “baseline study,” undertaken with the intent of establishing how students incorporate traditional representations into their explanations and, by extension, their understanding of chemistry (i.e., molecules and gases). The goal was to be able to identify representational practices that would inform the design of tools for the ChemSense learning environment.

Student pairs from a local high school were encouraged to "think aloud", to work together, and to make use of tools for creating representations as they explained chemistry problems. These tools were provided on the tables before them, specifically, paper and pens, molecular modeling kits, and other items for creating three-dimensional molecules (i.e., toothpicks, marshmallows, round-shaped candies.

We looked for evidence of students' meta or representational competence (diSessa, 1999; Kozma & Russell, 1997) in their discourse and manipulations of representations. Specifically, we wanted to find indications that students would do some of the following:

- See representations as corresponding in some way to ideas that explain phenomena.
- Identify and analyze features of a representation (such as a peak on a graph) and use them to explain, draw inferences, and make predictions about chemical phenomena or concepts.
- Generate their own representations or select a different representation or a set of representations for different purposes.
- Link chemical phenomena at the observable, physical level with an understanding of chemistry at the particulate level.
- Move fluidly back and forth among chemical representations at both the macroscopic and microscopic levels
- Evaluate representations and identify what they represent and fail to represent.

For the purposes of this paper, in the following sections we have identified examples of three of the characteristics of representational competence in our interviews of students' reasoning with chemical representations. We believe that this is the first step towards understanding how "meta" representational competence can be identified and taught as well inform our design of the ChemSense learning environment that we are developing.

Example 1: Using representations as part of their justifications

Science making is the social, exploratory, negotiated process by which scientists construct the tentative knowledge that is not widely accepted (Latour, 1987). Given this view of science learning, we wanted to see if our students would refer to features of their representations as backings, warrants and claims for their statements. Regardless of whether their statements are true, we believe that it is important for students to acquire a cognitive skill of thinking with the use of the representations that are being constructed.

In the following example a student uses a 3d model of a molecule to justify why the angle of the bonds do not change and then concludes that the molecule cannot have an alternative shape.

H: They're all the same.

Experimenter: They're all the same.

H: They're all going to pull each other the same.

Experimenter: Okay.

H: Cause these all have the same electric, electromagnetivity. It doesn't matter how much they push off each other. They're all the same so they're all going to push off at the same angle. So they're all going to go be exactly the same angle if you measure it.

Experimenter: So you could rotate this…

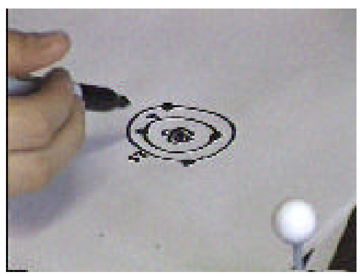
H: And it would stay exactly the same shape.

In this example the students' constructed model serves to provide a physical reality for the underlying structure of the angles of the bonds. In this way, the student uses the model as a justification for his statement that "they (bond angles) stay exactly the same shape."

In a second example a student uses his own previously constructed representations to explain orbitals to another student.

> ***H:*** And we've got like the orbital -- it's a circular shape.
>
> ***Experimenter:*** All right.
>
> ***H:*** And there's going to be two *(unintelligible)* exactly opposite sides… of each other. And that's gonna be like the hydrogen… actually, there's only like, one proton in there but that's okay! But, so that's what, all four of these hydrogens will look like. While with C, the whole atom will look, you've got the C here, it will look like *(drawing)* that inside. And then, it'll have its second P -- second S. I'm getting mixed up. And it'll have two here, also along this side and it'll probably go at exact angles to each other because it wants to get as far away.

"…it will look like that inside."



Second S

P Orbitals

> Experimenter: Okay.
>
> H: And then it has what's called P orbitals and they'll come out like this, like a big 8. And they have… and they're kinda like this shape. They go kinda off… one… they kinda go… tetrahydral shape.
>
> Experimenter: So you really need it -- it's hard to show on this?
>
> H: You can't. These are angles of a hun… six… what were the angles?
>
> M: (unintelligible)
>
> H: Like 180 or something between each one of them. And, when… so… you've got a total of one, two from here, one, two from here. That's the second S orbital.

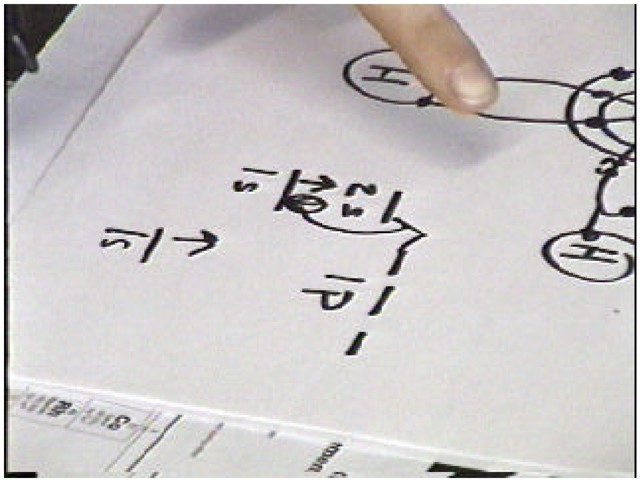
> And you've got four before you get to… to the P. So it's gonna be one, two, three, four.

In both of these excerpts the representations help the students think through and explain their justifications for their ideas. They are learning to "talk chemically" by taking a position and using the representations to support their ideas. It is interesting to note that our preliminary analyses of students' representations and explanations showed that students were better able to explain more complex ideas when they reasoned with the help of the representations as compared to reasoning without them. It is likely that aspects of the representations cue specific types of knowledge.

Example 2: Focusing on particular aspects of the representations

We believe that being able to explain particular features of a representation is an example of going beyond the surface level. In addition, comparing one feature of a representation to aspects of another is further evidence that they can move fluidly between multiple representations and to link them in meaningful ways. In the first excerpt a student compares specific aspects of one representation (bonds) with another representation instead of referring to each representation as a whole. In the second excerpt a student refers to the toothpicks of their model to explain what they represent.

> ***H:*** *(unintelligible)* when you use something like this, um, one S, two S, there we go, one - two - three, one - two, and what hydrogen has is it has one like that.
>
> ***Experimenter:*** And that represents what?
>
> ***H:*** One electron. And this is your spin. If you have one -- one electron going at one spin, going up, the other one automatically has to go down. So it's -- it wants to go up. There's going to be a space here. And when it bonds with this one, it does. So it gets down. Now if it was going to bond like this … bond here, this one, there'd be a new one coming in that has a one S like this also. This one doesn't have anywhere to go. So this one would have to jump up to the next level so this one moves in. And that takes a lot of energy to jump up the levels.



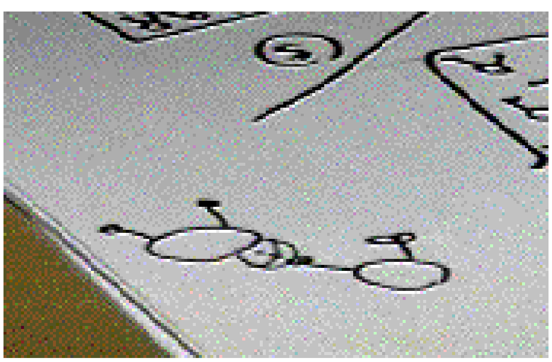
In the next excerpt a student explains that the toothpicks of 3d model represent the electrons and not just the connections or bonds.

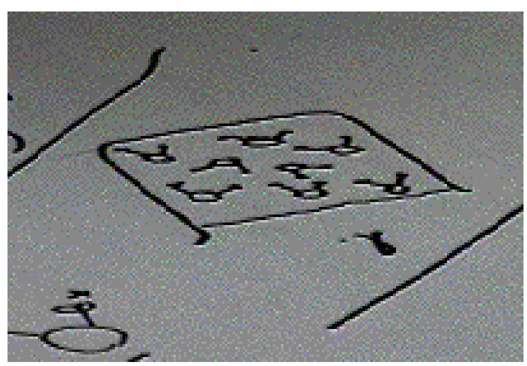
> ***Experimenter:*** Can you explain that?
>
> ***R:*** Okay. What this…
>
> ***Experimenter:*** Why don't you explain it since you made it?
>
> ***R:*** Yes, I'm sorry.
>
> ***M:*** This is like the… nucleus. *(points to parts of the marshmallow model)* This represents the oxygen and these two are the hydrogens and he said there are two, two, each, each toothpick represents two electrons… so… on this picture, there are two electrons with the hydrogen and the oxygen between them so these are two… they're two lone pairs… which kind of repel… the hydrogen… that's why it looks like this.

In the next example a student represents the idea of hydrogen bonding nicely and points out that the difference between a solid and a liquid is due to the amount of hydrogen bonding. Here the student focuses on a particular aspect of the representation and moves between the 3d model and their drawing. It is important to note that the student suggests that there is no hydrogen bonding in a liquid. This is not correct. In a liquid there is some hydrogen bonding, but not nearly as much as in a solid. Only a gas will not exhibit hydrogen bonding.

Experimenter: A hydrogen bond. What's a hydrogen bond?

G: It's like a… here's a picture of one… it's a bonding between two molecules like right here… this is the hydrogen bond…





Experimenter: So this end of the water molecule attaches to this end of the next one.

G: Yeah. Cause this… see how they're positive and negative…

Experimenter: Okay.

G: And these two are… and they attract together so they bond together.

Experimenter: Okay so this fills a nice pattern and they're all stuck together. Okay, makes sense.

G: And the other one for the liquid they're not so attracted to each other so they're all kind of going everywhere, I guess. It's just… they don't have any bonding together.

Example 3: Moving fluidly among different representations

It was also noted that students were able to link multiple representations and move fluidly back and forth among them. We believe that these are important aspects of representational fluency because students are recognizing that different representations serve different purposes and that the same phenomena can be represented in multiple ways.

For example, in the following excerpt a student is explaining single and double bonds to their partner and to the experimenter. In this case the student is prompted to move between a Lewis Dot Structure and a 3d model of their molecule.

Experimenter: Okay, so if I read this correctly I'd see four different bonds.

H: Mmhmmh. Once it breaks off it goes through the fourth bond. While with this, these we're just combining the different spaces. They might -- it doesn't really matter which one of the electrons combines.

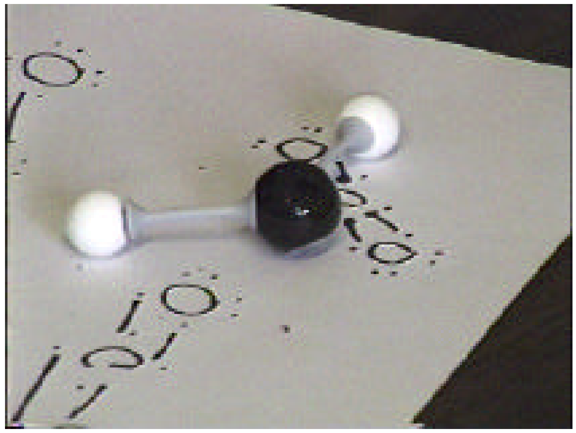
Experimenter: So comparing what you did here with what you have…

H: Well this is the original with diatomic *(unintelligible)* so you have four. It's alone until it comes over. It's like six. And then you *(laughing)*.

M: You should let me go.

Experimenter: And these are single in here? These are double?

H: Ah, they are a -- they're a covalent bond but they're single.



Experimenter: Okay.

H: The only time you see something like a double bond is like with um, oxygen with what? Sulfuric acid?

M: No.

H: No. It's really hard to think of what it would be. I don't know, um, something like this. That means double bond but these are single.

We present these three examples of representational fluency to promote the idea that students need to become competent at using and manipulating representations if they are to be able to move beyond the surface features of physical phenomena and rote manipulation of symbols. We believe that this kind of behavior is necessary for students to increase their knowledge of chemistry as well as to advance their understanding of the nature of scientific knowledge (i.e., epistemic knowledge). Gaining practice of representational use will help students see how models can be used to test ideas or to understand that knowledge can be treated as an object of inquiry and therefore become conjectural and not serve as a fact to be memorized.

We are currently developing a learning environment (ChemSense) to support the investigations and uses of representations in laboratory settings. We are building tools that promote representational practices as students engage in investigations in their chemistry classrooms.

PIE: DESIGNING FOR EPISTEMIC DISCOURSE AROUND CONCEPTUAL REPRESENTATIONS

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This section examines ways in which activities can be designed to prompt and support epistemic discourse. In particular, it looks at the potential for discussions in which students evaluate competing ways of reasoning about probability. The potential value for these types of discussions is illustrated by an example where the lack of consideration of conflicting epistemologies may have influenced and in some cases hindered students' conceptual development.

There are three well-defined ways of reasoning about probability and uncertainty. First, there is Subjective probability, which deals with the degree of belief or confidence in an uncertain statement or event. For example, one might say there is a greater probability that Los Angeles will get a football expansion team than Monterey. In this case one is expressing their respective degree of confidence in a one-time event. Second, there is Frequentist probability, which assigns probabilities based on the long-term behavior of random events. For example, one might calculate the probability of rolling a seven on two dice by rolling the dice, recording the results, and extrapolating from this empirical data. Third, there is Classicist probability, which assigns probabilities based on the quantification of all the equally likely possible outcomes that can happen (i.e., the outcome space). In this case the probability of rolling a seven on two dice is calculated by enumerating the thirty-six possible equally likely outcomes for two dice and counting the number of ways you can roll a seven (i.e., 6 out of 36).

Each of these ways of probabilistic reasoning has a long history and strikingly different epistemological commitments. Subjectivist probability considers knowledge itself to be uncertain. Frequentist probability grows out of the epistemological tradition of empiricism, which argued that we don't really know things, but we only know about things. From this perspective perception plays a critical role in how we come to know things. Knowledge is built through induction and hypothesis testing. Classicist probability, on the other hand, emerged from the rationalist tradition, which argued that knowledge is a rediscovery of universal truths. From this perspective, knowledge is constructed deductively from a priori truths and not one's empirically verifiable perceptions.

There is evidence that students, particularly young students, intuitively reason about probability from the Subjectivist perspective (Konold, 1989). From this perspective students see each trial of an experiment, not as one of many possible outcomes, but as the single outcome of the experiment (Konold, 1989).

However, from the perspective of some mathematicians as well as the mathematical standards for K-12 mathematics education the subjectivist perspective is a misuse use of the mathematical register because the term probability is restricted to refer to the long term trends and not single events. The national mathematical framework calls for students in the sixth through eighth grade to both, "develop and evaluate inferences, prediction, and arguments that are based on data" and also to "compute simple probabilities using appropriate methods, such as, lists, tree diagrams or area models," (NCTM, 1998, pgs. 237-239). That is, the NCTM framework calls for students to be able to reason both from the Frequentist and Classicist point of view.

The Probability Inquiry Environment (PIE) was designed as a three week probability curriculum for seventh grade students that marries these two perspectives. The PIE curriculum consists of a number of computer-based and hands-on collaborative inquiry activities that are designed to help students build from their existing understanding of probability. In each PIE activity students were asked to determine if a game of chance was “fair”. PIE provided a simulation of each game and a set of tools to help the students analyze the empirical data they generated. From the students' growing understanding of probability based on these long-term trends of their empirical data (i.e., Frequentist probability), PIE builds towards a way of reasoning about probability based on the more abstract concept of the outcome space (i.e., Classicist Probability).

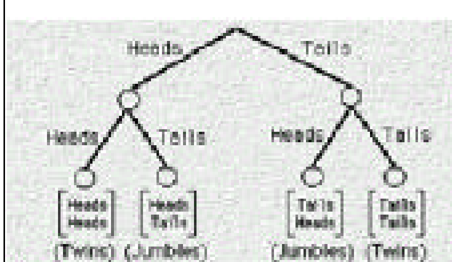
In PIE both the Frequentist and Classicist ways of reasoning are anchored by representations. Frequentist reasoning practices require representations of aggregated data such as bar charts, fractions, and percentages. This is necessary because it is difficult to perceive and reliably reason about long term trends without quantifying and representing the data in some manner first. Classicist reasoning practices, on the other hand, require representations of the outcome space such as ordered lists, tables, probability trees and area models. Like empirical data, to reason successfully from the outcome space it must first be represented. PIE was successful in helping students develop ways of reasoning around both types of conceptual representations. But for some students there was an unanticipated resistance to move from Frequentist to Classicist ways of reasoning that may be rooted not in their conceptual understanding but their epistemological beliefs.

Figure 5 shows two girls using their empirical data to inductively determine that the game they are playing is fair. In their talk they reference both that the number of points the two teams are scoring is close and that the two teams are winning about the same number of games. Figure 6, on the other hand, shows a student, in interaction with the teacher, coming to the same inference about the same game deductively, based on the idea that both teams have the same number of opportunities to score.

C	*at 200 points, the twins are ahead*
R	**By like two points! Three points** **[points to table of pts]**
C	*do you think the game is fair or unfair now?*
M	**I think it's fair**
R	**The game is**
C	*To play, press the start button.*
R	**'cause they won like, equal, you know.** **[Points to chart of games to 20 & games to 200]**

Typed: we think the game is FAIR because, they have won an equal amount

Figure 5: Rosa and Maria reason from their data



T	Let me ask you this. What if I just showed you this set up. And you didn't even play the game yet.... Bill, would you say fair game to start out?
B	Yeah
T	Why? If you just look at the set up of it
B	Because they each have an equal chance of winning. There's four ways that the coins can land. And the Jumbles can win two of them and the Twins can win two of them.

Figure 6: Reasoning from the outcome space.

These two ways of reasoning are then juxtaposed in a whole class discussion. In this debate many students begin to adopt the classicist perspective of deducing fairness based on the quantification of the outcome space. However, some students explicitly reject that it is a valid way of reasoning saying, "I wouldn't really know if its fair, but I wouldn't know if it is unfair either. It would be hard to tell until I played it." While by the end of the PIE curriculum most students had appropriated the Classicist perspective, a minority of students still held that they could not make predictions about future random events without first collecting empirical data first.

It is possible to speculate from this example that some of the difficulty that students have in successfully reasoning about probability is epistemological and not necessarily conceptual or development, as has been assumed (Konold, 1989; Metz, 1995; Piaget & Inhelder, 1975). If this is true, then an essential part of the students' learning trajectories is to critically examine these different reasoning practices. Comparing and evaluating these two reasoning practices, each anchored by a different set of conceptual representations, would help bring the students' own epistemologies to the forefront of the discussion.

Unfortunately, because we had not anticipated this particular difficulty we did not design activities that juxtaposed the two perspectives to encourage and support the debate. However, it seems that a useful design principle can be learned from our experience in the classroom. That is, it is useful to consider different ways of representing (and labeling) distinct forms of knowledge or reasoning practices so that they can be visually contrasted. This comparison of ways of reasoning and the types of conceptual representations that anchor these reasoning practices would allow students to engage in a debate about the respective merits of each. This in turn would help the students to address their own epistemological perspective and how it is related to different forms of mathematical reasoning.

OUTLOOK AND OPEN QUESTIONS

What do these various knowledge representations have in common and what are the epistemic practices they appear to support?

The knowledge representations we have described are of two types. ExplanationConstructor, SenseMaker, and Belvedere are explicit epistemic representations. They are each designed to structure students' expression of their thinking in ways that focus on epistemological aspects of arguments. Each is concerned with making knowledge claims explicit and publicly inspectable, and in representing claims and evidence as distinct. Their differences lie in the ways in which they represent arguments, and potentially therefore in the way they communicate the nature of scientific argumentation. One useful line of research with respect to such epistemic representations would examine how representational differences a) emphasize different epistemic aspects of scientific knowledge; and b) lead to different kinds of interactions with the representations and the consequences for epistemic practices.

The second type of representation, in PIE and ChemSense, includes discipline-specific conceptual representations. The epistemological aspects, or values if you will, are often implicit in such representations. The examples in each section of students using these representations to make arguments show that they can support valued epistemic practices, and illustrate how epistemological ideas are tightly interwoven with conceptual notions. An interesting line of research of these kinds of representations could be to consider how they might communicate epistemological ideas more explicitly.

We are not alone, of course, in our interest to design knowledge representations to support epistemic practices (Hawkins & Pea, 1987; Jackson et al., 1994; Scardamalia & Bereiter, 1993). We want to argue, however, that the goals and practices described here go beyond typical discussions of scientific reasoning to explicitly address how students' epistemologies of science can be developed, in addition to their understanding of science concepts and their ability to inquire into novel problems. To date, there has been scant research to try to link students' inquiry experiences in science to their epistemologies of science. One of us has found that students' ideas about the nature of theories, experiments, and their relations do not change after an inquiry-based unit (Sandoval & Morrison, 2000), while others have found that such changes occur only through targeted instruction (Carey et al., 1989; Smith et al., 1999). Finally, as we have suggested above, many of the efforts here have led to productive learning, both about specific science concepts and about processes of argumentation. More research is needed, however, to understand how particular representations support particular epistemic practices.

REFERENCES

Bell, P. (1997). *Using argument representations to make thinking visible for individuals and groups.* In Proceedings of CSCL'97: The Second Intl. Conference on Computer Support for Collaborative Learning.

Bell, P. (1998). *Designing for students' science learning using argumentation and classroom debate.* Unpublished Doctoral dissertation, University of California, Berkeley.

Bell, P., Davis, E. A., & Linn, M. C. (1995). *The knowledge integration environment: Theory and design.* In Proceedings of CSCL '95: The first international conference on computer support for collaborative learning, Bloomington, IN.

Bell, P., & Linn, M. C. (in press). Scientific arguments as learning artifacts: Designing for learning on the Web in KIE. *International Journal of Science Education*.

Brown, A. L. (1992). Design experiments: theoretical and methodological challenges in creating complex interventions in classroom settings. *Journal of the Learning Sciences, 2*(2), 141-178.

Brown, A. L., & Campione, J. C. (1998). Designing a community of young learners: Theoretical and practical lessons. In N. M. Lambert & B. L. McCombs (Eds.), *How students learn: Reforming schools through learner-centered education* (pp. 153-186). Washington, DC: American Psychological Association.

Carey, S., Evans, R., Honda, M., Jay, E., & Unger, C. (1989). 'An experiment is when you try it and see if it works': a study of grade 7 students' understanding of the construction of scientific knowledge. *International Journal of Science Education, 11*, 514-529.

Carey, S., & Smith, C. (1993). On understanding the nature of scientific knowledge. *Educational Psychologist, 28*(3).

Cavalli-Sforza, V., Weiner, A., & Lesgold, A. (1994). Software support for students engaging in scientific activity and scientific controversy. *Science Education, 78*(6), 577-599.

Coleman, E. B. (1998). Using explanatory knowledge during collaborative problem solving in science. *Journal of the Learning Sciences, 7*(3&4), 387-427.

Coleman, E. B., Brown, A. L., & Rivkin, I. D. (1997). The effect of instructional explanations on learning from scientific texts. *Journal of the Learning Sciences, 6*(4), 347-365.

Collins, A., & Ferguson, W. (1993). Epistemic forms and epistemic games: Structures and strategies to guide inquiry. *Educational Psychologist*, *28*(1), 25-42.

diSessa, A. (1991). Local sciences: Viewing the design of human-computer systems as cognitive science. In J. M. Carroll (Ed.), *Designing interaction: Psychology at the human-computer interface* (pp. 162-202). Cambridge: Cambridge University Press.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's images of science*: Open University Press.

Dunbar, K. (1993). Concept discovery in a scientific domain. *Cognitive Science, 17*, 397-434.

Duschl, R. A. (1990). *Restructuring science education: the importance of theories and their development*. New York: Teachers College Press.

Edwards, D., & Mercer, N. (1987). *Common knowledge : The development of understanding in the classroom*. New York: Routledge.

Guzdial, M., Hmelo, C., Hubscher, R., Nagel, K., Newstetter, W., Puntambekar, S., Shabo, A., Turns, J., & Kolodner, J. L. (1997). *Integrating and guiding collaboration: Lessons learned in computer-supported collaborative learning research at Georgia Tech.* In Proceedings of CSCL'97: The Second Intl. Conference on Computer Support for Collaborative Learning.

Hawkins, J., & Pea, R. D. (1987). Tools for bridging the cultures of everyday and scientific thinking. *Journal of Research in Science Teaching, 24*(4), 291-307.

Hewitt, J., & Scardamalia, M. (1996). Design principles for the support of distributed processes, *Paper presented at the Annual Meeting of the American Educational Research Assn.* . New York.

Hodson, D. (1988). Toward a philosophically more valid science curriculum. *Science Education, 72*(1), 19-40.

Jackson, S. L., Stratford, S. J., Krajcik, J., & Soloway, E. (1994). Making dynamic modeling accessible to precollege science students. *Interactive Learning Environments, 4*, 233-257.

Konold, C. (1989). Informal conceptions of probability. *Cognition and Instruction, 6*, 59-98.

Kuhn, D. (1991). *The skills of argument*. Cambridge, UK: Cambridge University Press.

Kuhn, D. (1993). Science as argument: Implications for teaching and learning scientific thinking. *Science Education, 77*(3), 319-337.

Kuhn, T. S. (1970). *The structure of scientific revolutions*. (2nd ed.): University of Chicago Press.

Latour, B. (1987). *Science in action*. Cambridge, MA: Harvard University Press.

Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: a review of the research. *Journal of Research in Science Teaching, 29*(4), 331-359.

Linn, M. C., Bell, P., & Hsi, S. (1998). Using the internet to enhance student understanding of science: The knowledge integration environment. *Interactive Learning Environments, 6*(1-2), 4-38.

Linn, M. C., & Songer, N. B. (1993). How do students make sense of science? *Merrill-Palmer Quarterly, 39*(1), 47-73.

Metz, K. (1995). Emergent understanding and attribution of randomness: Comparative analysis of the reasoning of primary grade children and undergraduates. *Cognition and Instruction, 16,* 285-365.

NCTM. (1998). *NCTM principles and standards for school mathematics electronic version: Discussion draft*. Reston, VA: NCTM Inc.

NRC. (1996). *National Science Education Standards*. Washington, DC: National Academy Press.

O'Neill, D. K., & Gomez, L. (1994). *The Collaboratory Notebook: A distributed knowledge-building environment for project-enhanced learning.* In Proceedings of Ed-Media 94, Charlottesville, VA.

Paolucci, M., Suthers, D., & Weiner, A. (1996). *Automated advice-giving strategies for scientific inquiry.* In Proceedings of Third International Conference on Intelligent Tutoring Systems (ITS'96), Montreal.

Piaget, J., & Inhelder, B. (1975). *The origin of the idea of chance in children*. New York, NY: W. W. Norton and Co. Inc.

Reiser, B. J., Tabak, I., Sandoval, W. A., Smith, B. K., Steinmuller, F., & Leone, A. J. (to appear). BGuILE: Strategic and conceptual scaffolds for scientific inquiry in biology classrooms. In S. M. Carver & D. Klahr (Eds.), *Cognition and instruction: 25 years of progress* . Mahwah, NJ: Lawrence Erlbaum.

Salomon, G. (1996). Studying novel learning environments as patterns of change. In S. Vosniadou, E. D. Corte, R. Glaser, & H. Mandl (Eds.), *International Perspectives on the Design of Technology-Supported Learning Environments* (pp. 363-377). Mahwah, NJ: Erlbaum.

Sandoval, W. A. (1998). *Inquire to explain: structuring inquiry around explanation construction in a technology-supported biology curriculum.* Unpublished doctoral dissertation, Northwestern University, Evanston, IL.

Sandoval, W. A., & Morrison, K. (2000). "You can't believe a theory if it's wrong": High school students' beliefs about theories and theory change, *Paper to be presented at the Annual Meeting of the American Educational Research Assn.* . New Orleans, April 24-28.

Sandoval, W. A., & Reiser, B. J. (1997). Evolving explanations in high school biology, *Paper presented at the Annual Meeting of the American Educational Research Assn.* . Chicago, IL, March 24-28.

Scardamalia, M., & Bereiter, C. (1993). Computer support for knowledge-building communities. *Journal of the Learning Sciences, 3*(3).

Schauble, L., Glaser, R., Duschl, R. A., Schulze, S., & John, J. (1995). Students' understanding of the objectives and procedures of experimentation in the science classroom. *Journal of the Learning Sciences*, *4*(2), 131-166.

Smith, C., Maclin, D., Houghton, C., & Hennessey, M. G. (1999). Can 6th-grade students develop a coherent constructivist epistemology of science? A comparative study, *Presented at the Annual Meeting of NARST* . Boston, MA, March 30, 1999.

Songer, N. B., & Linn, M. C. (1991). How do students' views of science influence knowledge integration? *Journal of Research in Science Teaching*, *28*(9), 761-784.

Suthers, D., Toth, E., & Weiner, A. (1997). *An integrated approach to implementing collaborative inquiry in the classroom.* In Proceedings of Computer Supported Collaborative Learning (CSCL'97), Toronto.

Suthers, D., & Weiner, A. (1995). *Groupware for developing critical discussion skills.* In Proceedings of First Intl. Conference on Computer Supported Collaborative Learning (CSCL'95), Bloomington, IN.

Suthers, D., Weiner, A., Connelly, J., & Paolucci, M. (1995). *Belvedere: Engaging students in critical discussion of science and public policy issues.* In Proceedings of 7th World Conf. on Artificial Intelligence in Education (AI-ED95), Washington, DC.

Suthers, D. D. (1999). *Representational support for collaborative inquiry*. In Proceedings of 32nd Annual Hawai'i International Conference on System Sciences (CD-ROM), Maui, Hawai'i.

Vahey, P., Enyedy, N., & Gifford, B. (in press). The probability inquiry environment: learning probability using a collaborative, inquiry-based, simulation environment. *Journal of Interactive Learning Research, 11*(1).

Wilson, S. M., Shulman, L. S., & Richert, A. (1990). 150 different ways of knowing. Representations of knowledge in teaching. In J. Caulderhead (Ed.), *Exploring teachers thinking* (pp. 104-124). Sussex, England: Holt, Rinhardt & Winston.