College of Education
UNIVERSITY OF WASHINGTON

The school science laboratory: Considerations of learning, technology, and scientific practice

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Paper prepared for the meeting:
High School Science Laboratories: Role and Vision

National Academy of Sciences, 12-13 July 2004

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Abstract

This paper explores the role of laboratory and field-based research experiences in secondary science education by summarizing research documenting how such activities promote science learning. Classroom and field-based "lab work" is conceptualized as central components of broader scientific investigations of the natural world conducted by students. Considerations are given to nature of professional scientific practice, the personal relevance of student's understanding of the nature of empirical scientific research, and the role of technology to support learning. Drawing upon classroom learning studies—especially those focused on scaffolding individual and social learning through inquiry experiences—specific insights about science learning through investigation are enumerated and detailed through instructional design principles. The affordances of novel learning technologies are discussed in some depth, especially computer simulations. The increasingly availability of information technologies in schools allow students to learn about contemporary scientific research and engage in inquiry at the frontiers of scientific knowledge. In sum, laboratory investigation holds significant promise for being able to support conceptual and epistemological learning when facilitating conditions are put in place for students.

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> "To many students, a 'lab' means manipulating equipment but not manipulating ideas."
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> — Lunetta, 1998, p. 250

> "[Students] encounter simulacra of the subjects and objects of science: science teacher in place of working scientists and technologists, textbook discourse in place of the spoken and written language of working science, 'school science' topics and information in place of those which might actually occur in any actual context of use or practice of science, school laboratory and demonstration equipment in place of the actual technologies in use everywhere else in our society."
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> — Lemke, 1992

1. Introduction: The Current Learning Context with High School Laboratories

Empirical research on the material universe leading to the advancement of parsimonious theory is a cornerstone of the natural sciences. Within the science curriculum, the role of student's laboratory work has shifted dramatically over the past century. There have been a broad variety of educational purposes ascribed to laboratory instruction and historically little consensus about how it can best support learning (cf. Lunetta, 1998; Lazarowitz & Tamir, 1994) although the situation seems to be improving (Hofstein & Lunetta, 2004; Millar, 2004).

One widespread approach to laboratory instruction has focused students on the confirmation of established scientific concepts, principles, and relationships through the execution of straightforward procedures fully specified by the curriculum developers with provided materials. Laboratory instruction focused on the unthinking confirmation of settled scientific knowledge amounts to what Schwab referred to as a 'rhetoric of conclusions' approach to science instruction (Schwab, 1962). When framed thusly, students frequently fail to engage in any meaningful form of inquiry. Their lab work amounts to empty, ritualistic procedures—the systematic execution of material procedures fully disconnected from their conceptual understanding of the associated subject matter. Perhaps it would be more apt to refer to it as a 'rhetoric of procedure' sort of approach. It bears a striking similarity to what Bruner referred to as "the 'meaningless demands' subculture of school" (Bruner, 1965, pp. 61-2).

This form of unproblematic, confirmatory lab instruction rarely attends to student's developing conceptual or epistemological understanding as they engage in inquiry. It also rarely makes systematic use of individual and social learning mechanisms associated with educational approaches that support student's development of scientific expertise (Bransford, Brown & Cocking, 2000). In this paper I will summarize the findings and pedagogical insights associated with select empirical learning studies that provide some insight into how lab instruction can be structured in order to actively engage students in development of disciplinary expertise.

The structure of the rest of the paper is as follows. Section 2 presents the organizing conceptual frame as *learner-centered scientific investigation*. This is a broadening of "lab work" in the sense that investigations include hands-on scientific experimentation or fieldwork as well as other epistemic dimensions of scientific inquiry associated with a specific investigation (e.g., arguing from evidence, interpreting data generated by other). It is also a narrowing of "lab work" in the sense that I constrain my focus to studies that involve instructional attempts to promote science learning specifically and empirically study the details of that learning. Section 3 presents a depiction of professional laboratory practice of scientists as a touchstone for thinking about the formulation of school laboratory experiences. I will argue that we need to worry about the gap between research science and school science—as the latter often departs significantly in kind from the former. Section 4 presents the principle substance of this analysis. Summaries of the research are organized around various kinds of epistemic activities associated with student's scientific investigations (in the broader sense laid out above). Section 5 then presents some conclusions, and I attempt to summarize the central themes of this analysis.

2. Focusing on learner-centered scientific investigations of the natural world

The educational goals and purposes that have become associated with laboratory and field investigations are manifold. This diversity of focus has led to a significant degree of fragmentation within the 'laboratory' literature as educational efforts and research analyses have concentrated their efforts on different uses and outcomes associated with student's laboratory activities (see Lunetta, 1998 for an historical review of these shifts and splits in the literature). A growing body of research has studied how students learn specific scientific concepts and relationships through engagement in specifically designed laboratory activities and inquiry processes. These are sometimes referred to as "the scaffolding studies" (cf. Metz, 1995) since they document the details of student learning, development, and interaction when they are systematically supported—or scaffolded—in social and cognitive learning processes. This research actively juxtaposes curricular and instructional design efforts with empirical studies of the resulting educational phenomena—often focused on details of learning. Through iterative cycles of educational design, enactment, and analysis, these design-based research efforts develop a detailed accounting of the educational phenomena relevant to the goals at hand and document principled design knowledge about how to promote innovative learning environments in real world educational settings (cf. Bell, 2004; Cobb, Confrey, diSessa, Lehrer & Schauble, 2003; DBRC, 2003).[1]

Not surprisingly, studying how students learn through laboratory-related activities has been a dominant focus of the scaffolding studies in science education. However, the educational focus on helping students *learn through scaffolded inquiry* results in the research being less about 'the laboratory' as a educational place (with specialized equipment and ritualized procedures) and more about supporting *learner-centered scientific investigation of the natural world.* In this educational framing of inquiry-based science education, laboratory-related activities are interwoven into inquiry sequences. The investigational practices that are promoted focus on framing research questions, designing and executing experiments, gathering and analyzing data, and constructing arguments and conclusions through a patchwork of investigational strategies in a way that more closely mirrors the investigational, 'knowledge work' work of scientists while simultaneously managing the learning processes of students.

This framing of learner-centered scientific investigation requires a more careful articulation in order to understand how it relates to the various ways in which laboratory work has been conceptualized in the science curriculum. I begin with the following definition and then unpack further each component element:

> *Learner-centered scientific investigations of the natural world* involve (1) engaging students systematically in *meaning making processes* (2) in conjunction with *sustained*

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[1] Given the complexity of coupling learning to educational design and teaching in particular classroom settings, scaffolding studies have historically been 'hot-house' efforts that focus on engineering educational innovation in specific classroom settings. A number of current design-based research efforts are currently pursuing how to bring educational innovation to greater scale within districts and across states.

scientific investigation of natural phenomena (3) through the *scaffolding of individual and social learning mechanisms* (4) in ways that *result in an improved understanding of subject matter, inquiry processes, the nature of science, and the role of science in society.*

The first essential element—engaging students in meaning making processes—distinctly separates this educational framing of laboratory activities from the aforementioned 'rhetoric of procedures' framing which students so often encounter in their curriculum sequences. Although it may seem a deceptively simple move in the reframing of laboratory activities, it is actually quite difficult to accomplish in practice since it is frequently competing with the dominant, 'knowledge-transmission' culture of schooling and hence it requires a complex educational intervention to bring it into place within a specific learning community. Drawing from both individualistic and social constructivist accounts of knowledge and knowing, this focus on meaning making recognizes that students can develop a deeper understanding of a subject and its broader relevance when they are given agency for articulating, deliberating, and refining their own understanding (Brown & Campione, 1998; Bruner, 1996; Linn, 1995). This is the fundamental 'constructivist' recognition of the ways in which we all refine our understanding through active cognitive and social processes; it stands in contrast to many efforts that have been framed in epistemological terms as 'the replacement of misconceptions' (Smith, diSessa & Roschelle, 1994).

The second essential element focuses on engaging students in sustained scientific investigation of the natural world. Although it can be quite challenging to accomplish, significant prior research has shown the learning benefits of 'in depth,' sustained investigation when students are focused on learning the more difficult concepts in a discipline (e.g., the nature of light, the distinction between heat and temperature, the relationship between force and motion, etc.) (cf. Bransford et al., 2000; Duckworth, 1991; Schmidt, McKnight & Raizen, 1997). This requires making use of laboratory work within longer sequences of sustained inquiry. There is also an emerging consensus from the scaffolding studies that the learning of scientific process and product are interdependent and are best accomplished through a pedagogical intertwining of these dimensions (Bell, 2004b; Metz, 1995; Reiser, Tabak, Sandoval, Smith, Steinmuller & Leone, 2001).

In *The Process of Education*, Bruner offers the foundational conjecture that "it is the underlying premise of laboratory exercises that doing something helps one understand it" (Bruner, 1960). Derived from the individualistic Piagetian view of the active construction of knowledge through inquiry that was emerging at the time—which fueled the central arguments of *Process*—it helped launch the subsequent 'learning through discovery' movement (cf. Bruner, 1960) and ultimately the recognition that discovery was being taken as an end rather than a means for knowledge construction (Bruner, 1965/1971). With the growing realization that unguided discovery alone did not frequently lead students to develop a deep understanding (see Brown & Campione, 1994) and coupled to the growing influence of a Vygotskian view of individual development through social processes in a cultural context, the instructional supports necessary to guide learning during problem solving and inquiry were first theoretically framed as forms 'scaffolding' in an empirical study of tutoring (Wood, Bruner & Ross, 1976). The theoretical notion of individual and social scaffolding for learning has become increasingly prevalent in the literature since, especially among researchers focused on the design of inquiry curriculum and learning technologies (cf. Linn & Hsi, 2000; Linn, Davis & Bell, 2004; Marx, Blumenfeld, Krajcik, Fishman, Soloway, Geier & Revital, 2004; Reiser et al., 2001). Attending to the manner in which students need to be individually and socially supported in learning allows for the articulation of educational design knowledge that connects educational design and teacher practice with student learning.

The fourth essential element recognizes that there are a broad variety of educational outcomes that can be associated with learner-centered scientific investigations. The learning of scientific concepts and principles are a central feature, however students also have the opportunity to learn about the processes of inquiry, the nature of science, and how scientific laboratory research fits into the broader contexts of society. These different outcomes are frequently pursued simultaneously. However, in considering the aforementioned focus on sustained, 'in-depth' inquiry and the zero-sum nature of the pedagogical effects of curriculum, it is often the case that focusing on one specific dimension takes time and effectiveness on another dimension (e.g., Schwarz, 1998).

3. The epistemics of scientific disciplines as a touchstone for construing student's scientific investigations

Fundamental aspects of the day-to-day 'knowledge work' of scientific disciplines is surprisingly absent from most precollege science curricula (Bell, 2004b; Lemke, 1992). Many scientists report not encountering "authentic" forms of scientific inquiry until they reached graduate school. Others first encountered it in research intern experiences—not in their coursework. As indicated by the quote by Jay Lemke at the start of the paper, we seem to have settled for presenting students with simulacra of science in ways that the images we present and the activities we promote have drifted quite far from professional scientific practice. This should concern us given that students likely make their professional life decisions based on the images of science they encounter.

Of course, the needs of learners are not those of professional scientists. But, there are parallels to be drawn between professional practice and school practice that are informative. I begin by summarizing aspects of professional laboratory and field work drawn largely from the 'laboratory studies' compiled in the anthropology and sociology of science literature:

- Scientists are frequently called upon to work through uncertainty in an unfolding investigation as they attempt to shift the status of knowledge claims from uncertain to certain (Latour & Woolgar, 1979/1986). They are often in the role of trying to "extract conclusions from incomplete or conflicting statements" (Hines, 2001). This 'window of uncertainty' associated with the day-to-day epistemic work is rarely presented to students although it does mirror features of their own knowledge construction process in the midst of inquiry (Collins, 1987).

- Scientist's lab and fieldwork are embedded in a broader context of inscriptional work associated with the communication and publication of results (Latour & Woolgar, 1979/1986). In many research labs, individuals frequently specialize in certain aspects of the endeavor. Divisions of labor are put into place in order to increase the productivity of the group. Although we typically want all students to encounter similar educational experiences, we often fail to carefully consider the broader purposes of student's scientific investigations. In situations where there is a authentic purpose to the inquiry (i.e., when it is more parallel to the authentic inscriptional work of scientists), students find more meaning in the laboratory work and their inquiry tends to qualitatively improve.

- The practical nature of investigation is also quite distinctive. It frequently involves: creating and tinkering with novel equipment (Hulse, 2003); extensive, coordinated use of technology (Knorr Cetina, 1995; Latour & Woolgar, 1979/1986); and learning from failures in order to achieve breakthroughs. Applied linguists have also studied the nature of 'research talk' taking place within scientific labs. They have found that private, informal talk is frequently subjective during investigations. For example, scientists seem to project themselves into their phenomena and talk 'through' it as they attempt to understand them (Ochs, Gonzales & Jacoby, 1996; Newstetter, Kurz-Milcke & Nersessian, 2004). When the research results move from private contexts to public ones, the discourse then shifts from personal *scientist* talk to more abstract *science* talk. Students are frequently held to more formal, rarified models of inquiry that differ significantly from these practical images of scientific practice.

- Laboratory work was once strongly confined to specialized spaces and select communities. That is increasingly changing. Lab work is blurring with the broader world as instrumentation becomes more ubiquitous (i.e., the world is becoming more of a lab) and as non-scientists have opportunities to become involved in the shaping of scientific questions (e.g., through the activities of NGOs and citizen science activities) (Latour, 2003). Citizens have significantly more opportunities to learn about and interact with contemporary scientific investigations than ever before.

These are relatively new images of scientific practice to be juxtaposing with the practical work of students. The purpose of presenting these images of scientific practice are to provide points of reference for decisions curriculum developers and teachers make in bringing particular images of scientific inquiry to students. These concrete images of scientific work are a viable image for aspects of the practical work of students during their scientific investigations. They are also informative as we try to compare the epistemics of scientists with that of students at the level of everyday practice. It seems that we often hold students to more abstract, idealized accounts of scientific investigation than those revealed through empirical study of professional scientists. There are important connections between the 'discovery work' of professional scientists and the 'knowledge construction' work of students. That is, I believe we can use these images to identify logical connections between the practices of scientists and students as the latter endeavor to engage in knowledge work that is similar in kind, if not in degree, to the former (cf. Smith, diSessa & Roschelle, 1994). At points of disconnection between scientific and school practice, we might carefully consider if school science has drifted too far from that of research science—or if the purposes of research science and school science differ such that the gap is warranted.

4. Research on core learning activities associated with scientific investigation

Historically, the science laboratory has been used to promote a broad array of educational outcomes.[2] For my purposes here I will frame outcomes in four categories: practical, social, cognitive, and epistemological. In ways that mirror professional scientific investigation, students need to learn how to conduct the *practical* details of the work itself—from the manipulation of equipment and materials to the formulation and execution of data collection plans as well as conducting relevant trouble-shooting along the way. Science investigations also open up thriving *social* contexts for collaboration and learning interactions. Students can develop an

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[2] Lunetta (1998) and Lazarowitz and Tamir (1994) detail these issues in depth.

understanding of how to conduct coordinated group work, how to communicate about ideas and negotiate shared understanding, how to manage divisions of labor and specialization, and how to aggregate and compare of results. Individual *cognitive* outcomes can also be pursued with regards to student's understanding of core disciplinary knowledge, disciplinary habits of mind, and an understanding of inquiry processes associated with scientific investigation. In terms of *epistemological* outcomes, students also develop images of science from their investigational activities and learn about their own learning. These can involve an understanding of the epistemic norms and practices of science—what counts as evidence, what kinds of arguments are compelling, what kinds of knowledge can result from investigations, and how such knowledge can help understand other contexts and social issues. Importantly, students can also be guided to develop a meta-understanding of how they learn across different contexts and how they can manage their learning (Hammer & Elby, 2003).

In the following sections I detail areas of consensus that summarize how students learn practical, social, cognitive, and epistemological outcomes from their scientific investigations. To do so, I largely draw upon the scaffolding studies conducted by researchers in the learning sciences field (Bransford et al., 2000). This is a sensible source to draw upon given the current educational context since these efforts are focused on how best to promote inquiry-based educational reform in specific educational settings. They detail what is practically possible under specific conditions. But, one important caveat is necessary. There is a broad consensus that educational innovations are systemic in nature (Bell, Hoadley & Linn, 2004; Brown & Campione, 1998; Salomon, 1993; DBRC, 2003). That is, educational innovations are more package-like in nature than being composed of discrete, essential elements. In other words, innovative forms of learning and interaction result from the enactment of a complex educational intervention involving hundreds upon hundreds of coordinated, pedagogical decisions. Therefore, the areas of consensus I present should be interpreted with the expectation that these relationships between educational design insights—presented in the form of design principles—and specific outcomes are embedded in the larger contexts of the educational innovations with which they are associated. These areas of consensus are the proverbial tips of large icebergs associated with these various packages of innovation.

Supporting conceptual change through meaning-contingent experimentation

Students should be actively manipulating ideas as well as equipment when they engage in scientific investigation. Although not common in many 'rhetoric of procedure' sort of construals of laboratory experimentation, a learning centered approach—where the prior and unfolding understanding of students are surfaced and taken into account during instruction—has been identified as a crucial feature of a broad number of educational approaches focused on scaffolding experimentation (diSessa & Minstrell, 1998; Duschl, 1990; Gunstone, 1991; Linn & Hsi, 2000; Minstrell, 2001; White, 1993). Two efforts well exemplify the benefits of this form of *meaning-contingent experimentation*.

Minstrell (1989; 2001) developed a comprehensive instructional approach to high school physics that put student's reasoning and ideas at the center of a guided experimentation curriculum. In this approach called facet-based instruction, students go through sequences of empirical investigation that are contingent upon their prior and evolving ideas about the subject matter. Through front-loaded formative assessments—involving conceptual elicitation questions within the context of 'benchmark lessons'—students are given opportunities to articulate and share their conceptual and procedural ideas in a socially safe group context. Students pursue subsequent investigations to specifically test and refine their ideas about core disciplinary knowledge, resulting in the development of normative understanding of physics in ways that outperform traditional physics instruction (Hunt & Minstrell, 1994). That is, the experimental sequence contingently unfolds in a way that best allows students to refine their individual understanding. Given regularities that exist in the range of student ideas about specific topics, much of the contingent experimentation associated with a facet-based instruction approach can be planned for and reused from year to year. In contrast to many misconception-centric approaches that assume that prior knowledge is overwhelmingly flawed and problematic for normative learning of disciplinary knowledge, the underlying research on student's facets of reasoning has shown that many of the "wrong ideas" held by students are generative when applied in different contexts. This approach is consonant with the knowledge refinement view of conceptual change (diSessa & Minstrell, 1998; Smith, diSessa & Roschelle, 1994). Minstrell and colleagues are also currently developing technological tools to be more broadly used to conduct facet-based instruction.

White and Frederiksen (White, 1993; White & Frederiksen, 1998) have been developing instructional approaches for the teaching of science through scaffolded investigation that they refer to as 'metacognitive facilitation.' Students learn about foundational aspects of inquiry and core knowledge of science through curricular sequences where metacognitive scaffolds are systematically integrated into student's inquiry. Scientific modeling is a core epistemic element to the approach. In their effort focused on the teaching of force and motion called ThinkerTools, they developed a curriculum unit where students engaged in cycles of scaffolded inquiry involving hypothesis work, empirical investigation, engagement with conceptually analogous computer simulations—of a game-focused microworlds variety—and refinement of a conceptual model for the phenomena. Across cycles of inquiry, the curriculum brought in increasingly conceptual complexity. They have demonstrated the benefits of integrating formative assessments throughout the instructional sequence in ways that students self-assess and reflect on core aspects of inquiry and epistemological dimensions of learning. From a study in twelve classrooms, students who knew the least about specific subject matter at hand benefited the most from this metacognitive facilitation instruction (White & Frederiksen, 1998). Students in the self-assessment condition benefited significantly more than control classes.

Two design principles can be formulated related to efforts such as these:

Design principle: Student's can engage in conceptual change on difficult topics when engaged in scaffolded meaning-contingent experimentation. That is, students can develop conceptual understanding through laboratory explorations, although it does require that the experiences include particular elements. The experiments pursued by students are designed based on what is known about student's understanding of the subject matter. Diagnostic, formative assessments embedded into the instructional sequences can be used to gauge student's developing understanding and to promote student's self-reflection on their thinking and understanding of the inquiry process. The interpretation of experimental results and subsequent theory (re)formulation activities are ripe contexts to support student's refinement of understanding (see also Clement, 1993; Duschl, 1990; Tien, Roth & Kampmeier, 2002).

Design Principle: With shared social norms for meaning-negotiation established in the classroom, students can learn to use the social context to share, deliberate upon, and refine their own ideas about scientific topics (Bell, 2004a; Linn & Hsi, 2000). In such situations, knowledge construction processes are also regularly influenced by the student's interactions with others in the social context. In these classroom situations the teacher plays a crucial role in providing time for adequate, equitable sharing of student thinking; for modeling a constructive interrogation of ideas; and shifting the agency of knowledge refinement to the entire community of learners (Minstrell, 2001; see also Brown & Campione, 1998). It is important to note that the cultivation of a community of learners requires substantial, concerted educational effort. Learning communities coming into place only over the course of months. Part of the complexity derives from the cultural norms of a learning community being at odds with central features of traditional school culture—and thus such communities are difficult to establish. Teachers need to shift into the role of learners who make their metacognitive processes visible to students. Students need to be supported in generative inquiry and be able to share conjectures and ill-formed ideas without fear of punitive judgment or ridicule. They need to be able to express and explore their ideas long enough to collectively explore them. In such communities of learners, laboratory experiences become a means by which students ideas are put to the test and refined.

Supporting conceptual change through student's engagement with rule-governed, interactive simulations

Computer models, visualizations, and simulations are increasingly pervasive within professional scientific investigation. The construction of computer models is a central epistemic practice associated with the study of many complex phenomena in the natural world. These models become durable representations of the theory-work of science. It is therefore sensible to want students to encounter similar computer models in their educational experiences. However, professional computer models, visualizations, and simulations are typically too conceptually abstract and technically complex for direct educational use (Gordin & Pea, 1995). Empirical studies of scientific practice have shown the complex interpretive practices that surround such representations (Latour, 1986). These associated interpretive practices of simulations become second-nature to those working with and creating the representations; such disciplinary noticing is a standard feature of expertise (Bransford et al., 2000). It then follows that students need to be supported in appropriating such disciplinary interpretive practices if they are to make use of such simulations. Of course, the situation is even more complex given student's developing conceptual understanding. For these reasons, however, the direct pedagogical use of scientific representations needs to include use of more learner-centered scaffolding than one might initially think. Custom simulations developed directly for educational use have also proven to be very beneficial.

Interactive computer simulations can be designed to reify otherwise abstract concepts and objects; they can allow students to personally explore the dynamics and interactive relationships associated with the modeled physical system through virtual investigation (Bell, 2004b; Horowitz, 1996; Kozma, 2003; Linn & Hsi, 2000; Roschelle, 1992; Snir, Smith & Grosslight, 1995; White & Frederiksen, 1998). It can be pedagogically powerful for students to more directly manipulate abstractions, to observe the theoretical consequences of their actions, and to interpret and assign meaning to the symbols and representations in the simulation that correspond to underlying concepts and principles (Horwitz & Christie, 1996; Kozma, 2003; Roschelle, Kaput & Stroup, in press; Linn & Hsi, 2000; White, 1993).

How should student's work with interactive simulations be embedded within their scientific investigations? Given the zero-sum nature of school curriculum, should simulations take the place of empirical investigation? Can students develop a similar conceptual understanding by working solely with simulations compared to direct laboratory experimentation?

The most successful uses of interactive, learner-centered simulations in the scaffolding studies have demonstrated the pedagogical utility of having students work with simulations in conjunction with their empirical investigation—as a context for the interpretation of embodied theory to be actively juxtaposed with the data and results of direct experimentation. These approaches stress the pedagogical leverage between laboratory experimentation and the exploration of simulations. For example, in the ThinkerTools curriculum students work with a computer microworld—which employs multiple, linked representations—after they have conducted and interpreted a related experiment (White, 1993). Student engagements with simulations, in conjoined use with empirical investigation, serve as a ready context for the refinement of conceptual understanding. They can serve as an ideal, complex artifact for collaborative learning conversations between small groups of students when they are collectively focused on interpreting the meaning of the rendered models and developing a shared understanding of them (Roschelle, 1992).

The following design principles follow from these studies:

Design principle: With proper design considerations taken into account, interactive simulations have the unique quality of being able to show conceptual interrelationships and connections between theoretical constructs and natural phenomena through the use of multiple, linked representations. Velocity can be linked to acceleration and position in ways that make the interrelationships pedagogically available to students (Roschelle, Kaput & Stroup, in press). Chromosome genetics can be linked to changes in pedigrees and populations (Horowitz, 1996). Molecular chemical representations can be linked to chemical equations (Kozma, 2003). The ability to make conceptual relationships visually and interactively available is a unique feature of simulations.

Design principle: Learner-centered, interactive computer simulations—when used as a supplement to hands-on experimentation—can support student's conceptual change. As opposed to thinking of simulations as a way of replacing laboratory experimentation, the most successful instructional approaches interleave student's engagement with the simulations with a series of empirical investigations and focus their attention on developing a shared interpretation of the simulations in small groups. As I will discuss in more detail later, simulations are typically gross simplifications of the natural phenomena. If simulations become the only way students engage with a particular phenomenon then there is distinct possibility that such simulations simply become the simulacra of science students are asked to engage with.

George Box provided us with the now famous dictum: "all models are wrong, some are useful" (Box, 1978). Under close consideration of this epistemological insight, I believe we should be significantly concerned by any educational effort that attempts to *only* engage students with simulated phenomena and rule-based, symbolic embodiments of theory. Now, of course, there are times when computer simulations are the only viable, safe, and efficient way to interact—albeit virtually—with a particular phenomenon (or rather, a programmed embodiment of a phenomenon). But when that is not the case, rule-governed, symbolic simulations provide such a "cleaned up" accounting of phenomena that we risk pulling students too far away from the fundamental nature of the phenomena itself and the texture of scientific practice. Students need experiences working through the ambiguities associated with work caught up in the "window of uncertainty" (Collins, 1987). They need to fret over practical and epistemological issues associated with data collection, measurement, and interpretation—issues of trouble-shooting, validity, error, replicability, and what not. As more and more educational design efforts provide computer simulations available online, we need to carefully consider the understanding of the phenomena and theory, and of science itself, that students develop through their engagement with such cleaned up accounts of the world. Data-driven models, or rule-based simulations that incorporate more realistic treatments of phenomena and the practicalities of data collection, might prove to be most educationally useful in that they maintain more fidelity to the natural world. This is also likely to be the case when more complex scientific models (e.g., those attending to hundreds of variables) are made educationally usable. At this time, we know very little about how students epistemologically understand computer models in science (see Schwarz, 1998 for a notable exception). Given the growing prevalence of computer simulations, we need more research to explore such issues.

Promoting an understanding of inquiry through reflective self-assessment

Do students develop a better understanding of scientific inquiry by engaging in such inquiry? It does not necessarily follow that this would automatically happen. Scholars studying student's understanding of the nature of science have spent significant energies on such issues. One view states that students do not automatically learn about the nature of science by engaging in inquiry; from this perspective, students need explicit instruction in the nature of science to learn about it. But there is significant ambiguity about how to best promote student's understanding of scientific processes.

Actively promoting student's metacognitive consideration of his or her own inquiry process in one promising approach (cf. Loh, Reiser, Radinsky, Edelson, Gomez & Marshall, in press); the approach shows what is possible under specific educational conditions. In the aforementioned study of the enactment of the ThinkerTools curriculum in those twelve classrooms (White & Frederiksen, 1998), the researchers also studied student's developing understanding of scientific inquiry using a pre/post inquiry test. In this assessment, students were engaged in a thought experiment that asked them to conceptualize, design, and think through a hypothetical research study. They compared gains in inquiry scores for students in the reflective self-assessment classes and control classrooms. They also broke out the results by students categorized as high and low achieving based on performance on a standardized test conducted before the intervention. Students in the reflective self-assessment classes exhibited greater gains on the inquiry test. This was especially true for low-achieving students. White and Frederiksen analyzed specific components of the associated inquiry processes—formulation of hypotheses, designing of an experiment, making up results, drawing conclusions from made-up results, and relating those conclusions back to the original hypotheses. Students in the reflective-self-assessment classes did better on all features of inquiry than control classrooms, especially on the more difficult inquiry dimensions (the latter few categories). These results demonstrate that active metacognitive facilitation during scaffolded inquiry helps students develop not only more expert conceptual knowledge but more sophisticated knowledge of inquiry processes.

Supporting conceptual change through student's explanation-driven analyses of data

Currently, the public has unprecedented access to vast collections of high-quality scientific data, and this trend can be expected to only expand over time. This is made possible through a confluence of technological innovation—increasingly ubiquitous data acquisition possibilities, centralized database collections served onto public information networks; and progressively greater Internet access among the citizenry. Extensive, distributed sensor networks are capable of streaming data into publicly accessible databases at rates of gigabits / second. Scientific fields have arranged for data resulting from empirical investigations to be normalized and aggregated (e.g., gene databases, astronomy image collections, global weather data). It is possible for students sitting in science class to access authentic and timely scientific data in unprecedented ways.

Although students may not be collecting the data they analyze in this form of scientific investigation, it shares many of the same learning goals of direct experimentation. It also represents an authentic practice associated with many corners of professional science—working with data collected by other researchers. It is important to note that the learner-centered design issues discussed above need to be deeply attended to as students are asked work with this data. Research continues to explore the educational design and learning issues associated with classroom uses of these vast data collections (Pea, Mills & Takeuchi, 2004). Existing scaffolding studies inform aspects of this form of student scientific investigation.

In the BGuILE project, students develop disciplinary-focused explanations of a culled data set about the micro-evolution of Galapogos finches (Reiser et al., 2001; Sandoval, 1999). The research demonstrated the necessity to scaffold student's data analysis processes (e.g., working from interpretations of instances of data to draw claims and formulate hypotheses for subsequent interrogation). It was also necessary to support consideration of relevant theoretical frameworks in which to be interpreting the data.

The WorldWatcher curriculum engages students in the interpretation of data about global climate issues (Edelson, Gordin, & Pea, 1999). A learner-centered visualization interface, coupled to classroom activities that help students understand the associated representational norms, allows for a meaningful interpretation of these complex data. The approach benefited from selecting a color-value mapped representation students had some cultural familiarity with.

Two design principles follow from these efforts:

Design principle: Learner-centered design issues need to be taken into account as students investigate authentic data sets. The interfaces used by professional scientists to access such databases tend to be too flexible and technical for successful student use. Successful scaffolding techniques associated with students developing a shared understanding of such data involve: bounding the space of possible data under consideration, scaffolding appropriate theoretical considerations, and promoting an understanding of the representational norms used in the visualization.

Design principle: Scaffolding disciplinary explanation of complex data helps students actively develop conceptual understanding and understanding of data analysis processes. The literature on the cognitive processing of information has generally shown the benefits of the active construction of understanding through self-explanation of information (Chi, de Leeuw, Chiu & LaVancher, 1994) and the social negotiation of understanding (Roschelle, 1992; Webb, 1989). Building upon these fundamental cognitive processes, focusing students on causal explanation and argumentation can help move them from a descriptive, phenomenological stance to one that considers theoretical issues of cause (Bell, 2004a; Sandoval, 1999). This is especially important with respect to phenomena with which students have extensive everyday experiences and yet normative scientific understanding is counter-intuitive.

In addition to having access to extensive online data sets, specific pieces of scientific instrumentation are also being made accessible online.[3] Scaffolding studies have not yet explored the education use of such remote instrumentation in student's scientific investigations. In the

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[3] For example, the following projects are providing remote access to instrumentation:
http://www.astro.uiuc.edu/stardial/
http://bugscope.beckman.uiuc.edu/
http://chickscope.beckman.uiuc.edu/
http://web.mit.edu/newsoffice/nr/2001/weblab.html

these interactions with remote equipment return data for students subsequent analysis, the pedagogical issues would mirror those described in this section. To the degree that it is logistically possible with specific pieces of remote equipment, these services allow students greater agency in posing and investigating research problems of their own design. This is in contrast to static databases that may or may not contain data that map onto student's research questions. A significant concern with remote instrumentation involves the difficulties in scaling up such an approach so as to be equitably available to all students.

A final note is warranted related to having students work with data given trends in technology development. Mobile technologies (e.g., PDAs, calculators) allow students to easily collect data during fieldwork outside of the classroom. Given unit pricing on such equipment, it also represents a more viable way to provide greater access to technology-intensive learning environments.

Supporting epistemological sophistication through argumentation and collaborative debate

Scaffolding student's scientific argumentation and collaborative debate also leads to other educational design principles associated with important epistemological outcomes.[4] First, by introducing argumentation through an exploration of a historical debate between scientists this allows students understand fundamental aspects of scientific argumentation—the creativity involved with theorizing and coordinating ideas and evidence, as well as how the ideas of an individual can shape their interpretations of evidence and constructed arguments. Second, it helps students realize they need to consider an entire corpus of scientific evidence—including related everyday life experiences, results from their experiments and fieldwork, and data and

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[4] See Bell (2004a) for a more comprehensive enumeration of learning results and design principles associated with the scaffolding of scientific argumentation and collaborative debate.

results from related professional scientific inquiry—rather than basing their beliefs and understanding on a subset of evidence. That is, it broadens their focus on integrating their understanding across a broader variety of experiences and experimental trials. Third, students come to realize that collaborative debates: (1) focus epistemic authority on the consideration of relevant evidence, (2) promote the social discrimination of relevant ideas, and (3) promotes their individual learning generally (see Bell & Linn, 2002 for details).

The WorldWatcher curriculum described above includes a focus on contemporary science by focusing in part on issues surrounding global warming. The growing public accessibility of professional scientific data and related research results allow for a broader consideration of topics that might be included in the school science curriculum. The overwhelming focus of science instruction on long since settled scientific knowledge overemphasizes historical topics and methods of scientific inquiry. Of course, much of this settled knowledge includes fundamental, core concepts and relationships of disciplines. However, in the overall scope of the science curriculum we should find considerable room for contemporary science topics and related student investigation so they can see contemporary images of scientific work and also come to appreciate current scientific enterprises that directly interface with contemporary social issues facing society.

In our research on the inclusion of contemporary scientific controversies in the science curriculum (Bell, 2004b; Hines, 2001; Linn, Bell & Hines, 1998), we have scaffolded student investigation of a range of topics from the frontiers of science—genetically modified foods, treatment and control of malaria, declining amphibian populations, and others. Conceptually relevant laboratory and field investigations conducted by students can be placed within the broader context of these contemporary scientific issues through the design of curriculum sequences focused on argumentation, debate, and role-playing (see Bell, 2004b for details). Scaffolding student inquiry into contemporary science issues presents an image of scientific knowledge construction that is dynamic and socially mediated within the epistemic norms of a community—at a micro level with the students in the classroom (as a scientific community writ small) and at a macro level with the broader scientific community (with the accumulation of settled knowledge over time and norms of scientific knowledge and communication). This is in stark contrast to the static, impersonal, and seemingly straightforward images of science that permeate much of standard science curricula. To some degree science curricula needs to depict the practice of contemporary science and its role in the pressing issues of society (cf. Collins & Shapin, 1986).

5. Summary

The school science laboratory encompasses a broad variety of forms, including disciplinary breadth (physics, life sciences, chemistry, earth sciences, interdisciplinary investigations) as well as historical breadth (from 18th century physics investigations to 21st century biotechnology procedures). The practical details of scientific work have continued to evolve. New technological infrastructures have been incorporated, interdisciplinary investigations have become more common, the applications of scientific knowledge continue to expand and intersect with the workings of society. School science investigations have not, by and large, kept pace. Efforts should be made to bring school science more in step with contemporary scientific practice (Bell, 2004b; Lemke, 1992). This includes showing how empirical investigation fits into the broader fabric of knowledge work associated with specific disciplines—engaging with the primary literature, communicating the research through presentations and publications, as well as applying laboratory-derived knowledge to societal issues as appropriate.

The overriding educational goals can be framed as providing citizens with: (a) images of scientific inquiry that help them understand the role of science in society and (b) experiences that help them develop sufficient disciplinary expertise such that it is personally relevant to their everyday activities. The learning studies summarized in this paper identify some of the established ways in which this is possible.

The dominant themes of this analysis can be summarized as follows:

- Student's scientific knowledge, inquiry knowledge, and epistemological understanding can be promoted by carefully attending to the meaning students construct associated with their scientific investigations of the natural world. Individual and social mechanisms for learning should be scaffolded to promote their learning during such investigations. Content and process dimensions of laboratory work are typically intertwined in these approaches.

- Laboratory work can be productively woven into the broader frame of scientific investigation that includes other modes of inquiry that mirror the epistemic contours of disciplinary activity. Explanation, argumentation, and debate provide activity structures for framing these more whole-cloth investigations.

- Learner-centered technologies can be designed to play a unique role in student's scientific investigations (e.g., interactive simulations). The tools and representations of professional scientific practice are typically not directly appropriate for these purposes. Successful uses of learning technologies generally supplement hands-on investigation with technology-based inquiry, rather than replace the former with the latter.

- Information technologies are opening up new possibilities for students to learn about contemporary science by working with data and results derived from such investigations.

- The gap between professional scientific practice and school science instruction needs to be carefully considered when construing student's laboratory investigations. Although the purposes diverge, there is an argument to be made for promoting epistemic fidelity between the two enterprises so students can develop images of science that bear closer relation to professional science. For this purpose, the concrete images of social and material dimensions of scientific practice offer significant insight (see Section 3).

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