# Instructional, Curricular, and Technological Supports for Inquiry in Science Classrooms<sup>1 2</sup>

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Inquiry is a central component of science learning (Lunetta, 1997; Roth, 1995). New approaches to science instruction feature inquiry as essential for student learning. The assumption is that students need opportunities to find solutions to real problems by asking and refining questions, designing and conducting investigations, gathering and analyzing information and data, making interpretations, drawing conclusions, and reporting findings. Congruent with recommendations by AAAS (1993), the National Research Council (1996) argues that "there needs to be a de-emphasis on didactic instruction focusing on memorizing decontextualized scientific facts, and there needs to be new emphasis placed on inquiry-based learning focusing on having students develop a deep understanding of science embedded in the everyday world."

Evidence indicates that students can attain deeper understanding of science content and processes when they engage in inquiry (e.g. Brown & Campione, 1994; Cognition and Technology Group at Vanderbilt, 1992; Metz, 1995). However, our work (Krajcik et al., 1998), along with that of others (Brown & Campione, 1994; Linn, 1998; Roth, 1995), has demonstrated that inquiry places many cognitive demands on learners so that they require considerable support to be successful. Students need support to become knowledgeable about content, skilled in using inquiry strategies, proficient at using technological tools, productive in collaborating with others, competent in exercising self-regulation, and motivated to sustain careful and thoughtful work over a period of time. Describing problems students encounter as they engage in inquiry and finding ways to ameliorate those problems has received considerable attention recently (Hmelo & Williams, [Special Issue, JLS], 1998; McGilly, 1994, Blumenfeld et al, 1998). In this paper, we describe inquiry in more detail, discuss ways to aid students via instructional, curriculum, and

<sup>&</sup>lt;sup>1</sup>. In Minstell, J. Van Zee, E. (Eds.) <u>Inquiry into inquiry: Science learning and Teaching</u>, American Association for the Advancement of Science Press, Washington, D.C. (in press).

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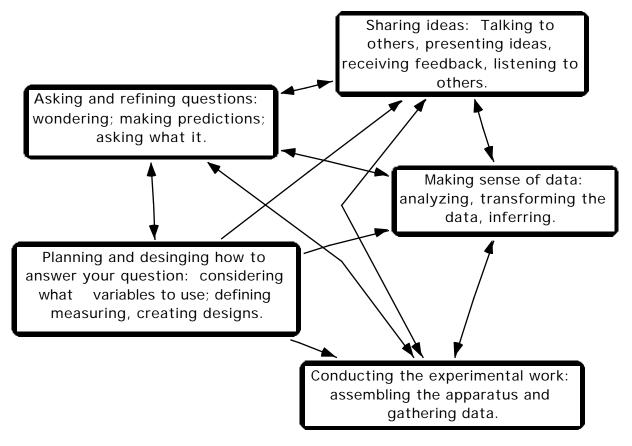
technological supports, and then illustrate how these have been applied to specific phases on inquiry where students encounter difficulties.

#### What Is Inquiry And Why Use It?

Broadly conceived inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work (NRC 1966). Inquiry involves making observations, posing and refining questions, seeking background information, planning and designing investigations, using tools to collect, analyze and interpret data, explaining and communicating findings. Inquiry is not a linear process. Phases interact; for instance, preliminary findings may result in a decision to revise the original question or to alter data collection procedures. Figure 1 shows a model of inquiry (Krajcik, et al., 1998).

Renewed interest in inquiry comes from research that shows that students' understanding of scientific ideas and scientific process is limited, so that those who do well on tests often cannot apply their knowledge outside the classroom. New approaches to instruction assign primary importance to the way in which students make sense of what they are learning, rather than focusing mainly on the way in which the information is delivered. The assumption of such constructivist programs (Fensham, Gunstone, & White, 1994) is that integrated and usable knowledge develops when learners create multiple representations of ideas and are engaged in activities that require them to use that knowledge. Inquiry promotes development, transformation and representation of ideas and helps learners understand how knowledge is generated in different disciplines. Moreover, the emphasis is on depth not breadth. Inquiry teaching highlights ideas and themes central to the disciplines. In addition, conversation with others is an important way for students to exchange information, explain and clarify their ideas, consider others' ideas, and expand their understanding.

Figure 1: The Investigative Web



From Krajcik et al., 1998

There are several instantiations of constructivist approaches that use inquiry; most include authentic tasks, artifacts, alternative assessments, technological tools, and collaboration. Our work makes use of projects, where students pursue investigations to answer a driving question related to their everyday experience. In finding answers to the question students learn scientific concepts, engage in scientific processes, and gain a better understanding of the discipline (Blumenfeld et al, 1991; Krajcik, Blumenfeld, Marx, & Soloway, 1994). Others rely on anchored experiences created on videotape (Sherwood, Petrosino & Lin, 1998). Constructivist approaches often emphasize the production of artifacts such as multimedia documents, models, presentations, or demonstrations. Producing such artifacts allows students to apply information and represent knowledge in a variety of ways. Assessment is closely tied to artifact development;

artifacts serve as a way for teachers to see how students are thinking, for students to share their ideas and receive feedback which can be incorporated into revisions. Moreover, rather than rely on standardized tests, which have been criticized for focusing on knowledge of isolated facts, the use of alternative assessments that have some value beyond the classroom is encouraged (e.g. Newmann & Archibald, 1992; Perkins, 1992). These assessments, such as public performances, creation of museum exhibits or reports to local groups, require students to exhibit mastery of the discipline and to integrate prior knowledge with new knowledge.

Tool use is another core element of these approaches. Recent interest has centered on the use of learning technologies, such as interactive video technology (compact discs or videodisks), telecommunications, microcomputer-based laboratories, modeling and the World Wide Web. Learning technologies can help learners solve complex and ambiguous problems by providing access to information and opportunities to collaborate, investigate and create artifacts. Tools can extend and amplify learners' thinking because they reduce the cognitive load for students, moving some routine tasks like calculating, creating graphs, or depicting data in different forms from students to the computer (Salomon, Perkins & Globerson, 1991).

Collaboration and conversation also are stressed. Collaboration involves students building shared understandings of ideas and of the nature of the discipline as they engage in discourse with their classmates and adults outside the classroom. As students engage in conversation, they draw on others expertise, appropriate the knowledge of others, reflect on their own ideas, and internalize modes of knowledge and thinking represented and practiced in the subject area (Bruer, 1994). For instance, each school subject has a special vocabulary, a body of knowledge, and methods for gathering evidence and evaluating results that novices need to acquire.

# **Supports for Inquiry**

Below we discuss supports that can help students in the inquiry process. These include instructional supports, curriculum supports and technological supports. These can work

independently as well as in conjunction. We consider how each might be used to help students during inquiry and determine how combinations can enhance student ability to be successful.

#### **Instructional Supports**

During inquiry the teacher serves as a guide or facilitator as well as a learner. Benchmark lessons (Krajcik, Czerniak & Berger, 1999) are used to introduce students to relevant content and skills before and during inquiry. In addition, the teacher helps students develop thinking strategies similar to those used by experts, like heuristics for generating questions or interpreting data. They also help students become more metacognitive, attentive to planning, monitoring work and evaluating their progress. Below we review several ways teachers can support students, including scaffolding, using prediction, observation, explanation cycles, helping students develop concept maps and encouraging writing.

Scaffolding. Collins, Brown, and Newman (1989) use the analogy of a cognitive apprenticeship for the teaching-learning situation. The teacher scaffolds instruction by breaking down tasks, using modeling and coaching to teach strategies for thinking, provides feedback that helps students analyze their thinking diagnose their problems, and gradually releases responsibility to learners to perform these functions on their own. The emphasis is on helping students to become more like experts in their thinking about generating questions, using strategies to design inquiry to find solution to questions and evaluating the results of their efforts by mirroring heuristics and strategies that experts have been found to use, rather than on simply teaching skills. These types of scaffolds can be used during each phase of inquiry.

Krajcik, Czerniak and Berger (1999) offer these definitions and examples of scaffolds.

- Modeling is the process by which a more knowledgeable individual illustrates to the learner how to do or think about a task. For example, a teacher could demonstrate how to use the concept of "mean" to analyze data or how to read a pH meter. Many science processes, can be modeled for students. Some of these include illustrating for students how to ask questions, plan and design investigations, or form conclusions.
- Coaching involves providing suggestions and asking questions to help the student improve knowledge or skills. For example, a teacher could make suggestions to a student about how to make more precise measurements when reading a spring scale. Other forms of coaching can include asking thought provoking questions (such as "How does your data support your conclusion?"), giving students sentence stems (for example, My data supports my conclusion

- because...), and supplying intellectual or cognitive prompts (such as asking student to write down predictions, give reasons, and elaborate answers).
- Sequencing is breaking down a larger task into step-by-step sub-tasks so a learner can focus
  on completing just one sub-task at a time rather than the entire task at once. For instance, the
  teacher might break down the process of investigations into various components and not
  allow the learner to proceed to the next step until completing the previous step. For example,
  the teacher could require the learner to complete a plan before moving on to building an
  apparatus.
- Reducing complexity involves hiding complex understandings or tasks until the learner has mastered simpler understandings or sub-tasks. The classical example here is helping a child learn to ride a bicycle by using training wheels. In science classrooms, this might mean a teacher uses an analogy to reduce the complexity of a concept. For instance, the teacher could compare DNA to the instructions for building a model airplane.
- Highlighting the critical features of a concept or task is another way a knowledgeable other
  can support the learning of another person. For instance, a teacher could point out to young
  students that animals called mammals all have hair hair is a key feature. As another
  example, in teaching a student how to focus a microscope, the teacher might point out that a
  basic step in focusing the object on the slide is to always start with the lowest powered lens
  first.
- Using visual tools can help students understand a concept or task (Hyerle, 1996; Parks & Black, 1992). Visuals tools are pictorial prompts that help students understand their own thinking process. Visual tools also help make abstract ideas more concrete by organizing ideas or illustrating relationships. For instance students could use a computer simulation that represents the particle nature of matter to develop understandings of kinetic molecular theory.

Prediction, Observation, Explanation Cycles. In addition to scaffolding there are other instructional techniques that can help students. One frequently used technique that promotes linking prior and new knowledge is the prediction, observation, explanation cycle (POE) (White & Gunstone, 1992). Students are asked to draw on prior knowledge to make predictions about what will occur during a demonstration, what they might find when searching for information, or what the results of an experiment might be. They can make individual predictions, share them with a group, discuss reasons for their predictions and come to some consensus about what might occur as they exchange ideas. Teachers can also make a prediction, thinking aloud to model how they draw on what they know to determine what might happen, or coach students as they consider possibilities, pointing out things to consider. Next students observe the phenomena and record their observations. As in the prediction phase, students can make individual observations, share them with a group, and come to some consensus about what they observed. Teachers provide scaffolds by demonstrating how they record and organize data or help students reduce

complexity of complicated observations by creating charts or how they insure that the data are complete and correct. Finally, students compare their predictions to the observations and develop explanations about inconsistencies. Here again teachers can model how they generate explanations and consider whether the explanation is adequate, coach students as they develop explanations, and highlight various key features to consider. The point is to emphasize justification and exchange of ideas.

Concept Maps. Concept maps are visual representations of the relationship among ideas. The maps are organized hierarchically with most important and inclusive concepts at the top. Related ideas are clustered around the overarching concepts and are linked. Maps are judged based on accuracy of the hierarchy and linking of ideas. Such mapping helps students organize, structure, and connect information and results in more meaningful understanding of ideas. Mapping also aids in the retrieval of and facilitates the transfer of ideas to other situations (Eggen & Kauchak, 1992).

Novak & Gowin, 1984 created the concept map as a tool to assess changes in learning. However, in addition to assessment, concept mapping can be used for a variety of other purposes during inquiry. Concept maps can be used to elicit student understandings prior to exploring a question. They are also an excellent way for students to track concepts that are being explored during inquiry. As the investigation continues, students make new concept maps that integrate new information with previous understandings. By comparing earlier and later versions of their maps, students can see how their conceptual understanding is developing. Another useful approach is to have students compare their concepts maps with those of other students; to discuss and resolve differences. Conversational aids developed by Coleman (in press) to improve small group discussion of ideas and quality of explanations during the construction of concept maps are described in the section on collaboration.

Writing. Writing is another way to enhance student understanding. As students write they must retrieve, synthesize, and organize information. In addition, production of a written document requires learners to clarify their thoughts in order to communicate their understandings

to others in a comprehensible fashion (Santa & Havens, 1991) and also provides teachers with a window on student thinking. Keys (1994) showed that using collaborative writing guided by a series of prompts during the POE cycle resulted in improved reasoning with respect to drawing conclusions, formulating models and composing explanations that synthesized prior knowledge, observations and other sources of information.

As in other fields, journals are one form of writing that is receiving considerable attention in science education (e.g. Audet, Hickman, & Dobrynina, 1996; Britsch & Shepardson, 1997).

Bass & Baxter (1998) studied how fifth grade teachers made use of such notebooks, such as to write and draw, as a way to take notes, record observations, practice science skills, summarize information and as a resource for teachers to monitor task completion, assess understanding of specific concepts, and provide feedback. They found that teachers often controlled the writing, dictating what should be included and how, rather than use the writing as a way for students to work through and demonstrate their understanding. For instance, the authors determined that the notebooks were used to record procedure and findings rather than to explain conclusions and reasons for them and underrepresented the types of conversations students had about strengths and weaknesses of different methods and about the meaning of their data. The authors argue that for notebooks to actually fulfill their potential students should be asked to record their decisions and explain their thinking, keep track of their ideas and points made in conversations, and in general, focus on substance not simply procedures.

#### **Design Of Curriculum Materials to Support Inquiry**

In response to educational recommendations, there have been many new curricular packages designed to promote inquiry, which also incorporate technology. Examples include Scientists in Action developed by the Cognition and Technology Group at Vanderbilt (Sherwood, et al., 1998), Linn's (1998), Computers as Learning Partners, Songer's (1993) Kids as Global Scientists, and Edelson's (1998) WorldWatcher. Evidence indicates that these approaches help students achieve deeper understanding (Under the auspices of the Center for Learning Technologies in Urban Schools, The University of Michigan in collaboration with Detroit Public

Schools is developing yearlong curriculum materials for middle school students. The design principles<sup>3</sup> underlying these materials incorporate learning theory, our own experience, and the experience and suggestions of teachers and professional educators. The curriculum materials are organized into projects that promote understanding of science concepts via inquiry, are predicated on constructivist principles (Marx, Blumenfeld, Krajcik & Soloway, 1997), and address the needs of diverse students (Atwater, 1994; Ladson-Billings, 1995). The following design principles are the basis for curriculum materials.

- 1. Standards based. Materials are designed to meet District curriculum guidelines, which are congruent with AAAS' Benchmarks (1993) and the National Research Council's standards (1996).
- 2. Contextualization. A "driving question" that draws on students' experiences contextualizes scientific ideas and makes inquiry authentic. In the process of exploring answers to the question, students encounter and come to understand these scientific ideas. Therefore, the question must encompass rich scientific content so that it is intellectually worthwhile. It is chosen with the advice of teachers, parents, and content experts. For instance, students study chemistry by investigating the question, "Why does our air smell bad and is it bad for us?"
- 3. Anchoring. Students begin exploring the question via a common experience they can refer back to during the course of the project. These experiences, like collecting and analyzing samples of water from the local river, help to concretize or anchor the question (CTGV, 1992).
- 4. Inquiry. In exploring the driving question, students raise questions, design investigations, apparatus, and data collection procedures, gather and analyze data, and present results (Krajcik et al., 1998).
- 5. Technology tools. Each project is designed to incorporate technology tools that are most appropriate for finding solutions to the question. For instance, in the project "Why do I need to wear a bicycle helmet?" students use motion probes to explore distance-time graphs and velocity-time graphs. In "What is the quality of water in our river?" students use Model-It to create relations between various factors affecting water quality and use probes to monitor the water.
- 6. Collaboration. Students work with peers and with others outside the classroom. They communicate with community members, university students, and students in other schools to find information, share their ideas, data and conclusions, and receive feedback.
- 7. Community involvement. The questions on which students work mesh science with issues that are likely to be of interest to community based organizations and to the family such as environmental quality and disease. Community based organizations serve as sources of information about local problems, about local expertise with respect to the question under

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<sup>&</sup>lt;sup>3</sup> These principles are being instantiated into the curriculum by a team including Margaret Roy, Jon Singer, Becky Schneider from the University of Michigan and Karen Amati from Detroit Public Schools.

- study, as sites where students access technology after school, and as audiences for students work.
- 8. Scaffolding. The curriculum materials are scaffolded within projects so that students are introduced to concepts and to science processes in a manner that guides their learning. The teacher, the structure of the tasks, and the technology, provides scaffolds within a project. Teachers are given suggestions about when to model, coach, give feedback and present benchmark lessons. Tasks are structured to reduce complexity so that certain concepts or inquiry strategies are highlighted and questions that foster thoughtfulness are provided. The emphasis is on modeling of skills and heuristics, such as how to evaluate question quality, how to create charts to keep track of data collection or how to represent data in different ways. Technology scaffolds students by providing multiple representations, hiding complexity, and ordering and guiding processes (such as planning, building and evaluating).
- 9. Sequencing. The curriculum materials also provide support for students by sequencing inquiry processes and scientific concepts. Early in the middle school years, projects are structured tightly to minimize task complexity. Tasks are chosen to illustrate particular inquiry strategies and the enabling power of technologies. This tight structuring affords students the opportunity to experience all phases of the inquiry process and to build an understanding of how all the phases fit together. Later students are given more responsibilities for designing and conducting investigations on their own. Projects also are sequenced so that throughout the middle school years concepts are revisited. As a result, students develop rich understandings of how ideas are related to each other and to different scientific phenomena.
- 10. Artifacts Development. Throughout the projects students create a variety of artifacts such as investigative designs, plans for data collection, laboratory notebooks and models that both represent and help build understandings. These artifacts serve as embedded assessments by the teacher. Also, they can be shared, critiqued and revised to further enhance understanding. Students also create final artifacts such as oral or written presentations or multimedia documents that are exchanged with classmates, and with others in the school and the community. Having students demonstrate their learning in ways that go beyond the classroom is one feature of authentic instruction (Newman & Welage, 1993). Detailed rubrics assist teachers in evaluating artifacts to gauge student understanding.

#### An example project

In a project on motion and force students explore the driving question "Why do I have to wear a bike helmet when I ride my bike?" During this 8-week unit, designed for eighth graders, students inquire into the physics of collision. It begins with a dramatic short videotape illustrating how bike accidents can result in brain injury. Then a series of demonstrations using an unproctected egg riding a cart, representing a student riding a bicycle, to illustrate the possible results of a collision. This demonstration is revisited periodically throughout the project and serves as the anchoring experience that students return to as they explore concepts of inertia, velocity, acceleration, force and the relationships between them. It is also the focus of the final

artifact; students design a helmet to protect the egg during a collision to demonstrate their understanding of these ideas.

Students participate in several investigations supported by technology while exploring aspects of the driving question. They design experiments to examine the relationship between mass and inertia. Students study velocity and acceleration by collecting real time data using motion probes, which allows them to see these data immediately on the computer screen. They also learn how to read and interpret motion graphs. An investigation of gravity and mass involves collecting and interpreting data with the use of photogates to determine velocity. Students use motion probes again in designing and testing their egg helmets. These designs and the results of the testing are presented and discussed with the class. We also encourage the teacher to invite visitors from local safety and community organizations who attend the presentations.

#### **Technology design to support inquiry**

Although inquiry can be done in classrooms without the aid of technology, learning technologies expand the range of questions that can be investigated, the types of data and information that can be collected, the types of data representations that can be displayed to aid interpretation, and the types of products that can be created by students to demonstrate their understandings. With such tools, students can gather information about their questions on the WWW, collect real time data using probes and other portable technologies, make models, graphs and tables as a means to visually display data and quickly compare different results, and illustrate their understandings in a variety of ways (e.g. multimedia presentations). Moreover students can work collaboratively with others in and outside the classroom. Examples of these tools are Knowledge Integration Environment developed at University of California--Berkeley (Linn, 1998), and Worldwatcher, developed at Northwestern University (Edelson, 1998). The systems are integrated, designed to promote different areas of inquiry and allow for sharing. The tools are not specific to any particular content and they can be used to solve a range of problems and concepts. Because they can be used in different science classes across different grades, students

can become proficient users of the tools and knowledgeable about the processes of inquiry they support. The Investigator's Workshop described below is an example of learning technologies developed at the University of Michigan.

The Investigators' Workshop. The Investigators' Workshop<sup>4</sup>, is a suite of computational tools, based on learner centered design (see next section), developed to enable sustained inquiry (Soloway & Krajcik, 1995). As described in Table 1, the tools support data collection, data visualization and analysis, dynamic modeling, planning, information gathering from the University of Michigan digital library and the Internet, and web publishing (Jackson, et al., 1996; Soloway, 1997; Soloway & Krajcik, 1993; Soloway & Krajcik, 1996; Wisnudel et al., 1997). These tools have been revised several times based on studies of how students use them, the supports needed, and the types of artifacts produce by students.

The tools work together to support each phase of the inquiry process. For instance, when students are exploring the quality of a local stream, river or lake, they can use probes (e.g., pH, temperature, dissolved oxygen, pressure) attached to portable technology and accompanying software to carry out real-time data collection. The data can be uploaded to DataViz, where students can determine relationships and patterns using statistical analysis tools. The features allow students to visualize multiple types of data using a variety of techniques such as digital photographs, graphs, and text. In addition, students can link to representations and available animations to view the dynamic changes in different types of data.

4

<sup>&</sup>lt;sup>4</sup> The development of the Investigators' Workshop has been supported by grants from the National Science Foundation: (NSF Grant numbers REC 9554205 and REC 955719)

**Table 1 The Investigators' Workshop: Scaffolded Tools For Learners Engaged in Sustained Science Inquiry** 

Name	Function	Inquiry Support
Artemis	Supports on-line search and information gathering and evaluation using the UM Digital Library & Internet.	Information gathering and evaluating
Middle Years Digital Library Website	Provides support to students and teachers for carrying out on-line search activities to support inquiry.	
Portable computers and probes	Microcomputer-based laboratories for portable computers; allows students to collect experimental data outside classroom by connecting various probes to the serial port.	Data gathering
RiverBank	Water quality database tied to GREEN's field guide to water monitoring.	Data sharing and storage
DataViz	Data visualization tool; supports students as they strive to see relationships and patterns both in self-collected and data gathered from on-line sources using visualization and analysis techniques	Data visualization and analysis
eChem	3-D molecular visualization tool; allows students to easily build 3 dimensional representations of complex molecules. Future developments will allow students to link structure of the molecules to physical and chemical properties.	Molecular visualization
Model-It	Modeling tool for dynamic systems; allows students to easily build, test, and evaluate dynamic qualitative models	Dynamic Modeling
Web-It	HTML conversion tool to enable students to easily publish on the WWW.	Web publishing

Also, students can use Artemis, an interface to the University of Michigan Digital Library, to find and evaluate information related to their driving question. The digital library contains selected materials that are at appropriate levels of difficulty for middle and high school students with respect to reading and information complexity. Supports in Artemis allow learners to sort, select, and organize documents and then easily return to them for further work.

Students can then use Model-It to easily build, test, and evaluate qualitative, dynamic models. Students can import the functional relationships they developed in DataViz. Students plan their models by recording ideas, and creating objects and factors. Next, they build relationship links between the factors using qualitative and quantitative representations. A graphical view of each relationship is also provided. For data visualization, Model-It provides meters and graphs to view factor values. As students test their models they can change the values of factors and immediately see the effects. Finally, students can use Web-It to publish their results on the Web.

Learner Centered Design. We have learned a considerable amount about creating technology tools to support learners at different levels of expertise. The principles of learner centered design (LCD) (Soloway, et al., 1994) recognize the fact that students differ in a number of ways from professionals who use computational software. Students do not initially know the content they are exploring so that they must be supported as they engage in inquiry. Students also differ from each other in terms of technological expertise and in how they prefer to learn; therefore, the tools must be adapted to different levels of complexity and represent information and data in multiple ways. Finally, whereas professionals in a field are committed to their work, students often are not similarly motivated. Technology must help sustain engagement by scaffolding complex computational activities in order for studentst to focus on substantive cognitive issues and problem solving.

The incorporation of learning supports or scaffolding which addresses the differences between learners and professionals is central to LCD. Scaffolding enables the learner to achieve goals or accomplish processes that would otherwise be too difficult to obtain by guiding the selection of goals and processes. Our software incorporates three types of scaffolding. Supportive scaffolding guides learners through steps within phases of inquiry; e.g., when constructing a model students are reminded to make a plan of variables to include before building and testing. Reflective scaffolds support learners' metacognitive activities. For instance, they are prompted to test individual relationships or a sequence of relationships before

evaluating the entire model. Functionality in the software supports testing and debugging, allowing students to determine which relationships work and which may need revision. Intrinsic scaffolding supports different levels of user expertise; it makes the simplest level of functionality available to the novice learner, but allows learners to access advanced features as their capability grows. For example, at first students build qualitative models; but as they gain experience they select a weighting tool to make their relationships quantitatively more precise and accurate.

## **Supporting phases of inquiry**

In the next section, we explore some of the challenges students face in carrying out the various phases of inquiry and possible explanation for these challenges. We also highlight the difficulties teachers will face in supporting students in the various phases of inquiry and we suggest strategies teachers can use to help students.

#### Asking questions.

Good questions are both feasible to investigate and scientifically worthwhile, so that in exploring the answers students learn important science concepts. For instance, one class was working on a project "Where does all our garbage go?" and conducting experiments on the effect of worms on decomposition. Groups of students were asked to generate sub-questions and to design their own investigations. One group of students asked the question: "Which types of material decompose and which don't in light or dark, with worms?" This question meets the criteria of a good question because it allows students to explore important content addressed by the project, because students can design an experiment to answer their question. To answer this question students needed to set-up an experimental situation to test the impact of light on a decomposition environment.

However, several studies have shown that initially student questions do not reflect these criteria. Students ask questions that require little effort to answer and are primarily factual or require yes/no answers, rather than questions that can extend their understanding of a topic (Erickson & Lehrer, in press; King, 1990; Scardamalia and Bereiter 1992). Similarly, Krajcik et

al. (1998) found that seventh graders often used personal interest and preferences as source for questions; the selection was not tied to scientific merit of the questions but rather to an attraction to some aspect of the situation or phenomena. They chose questions about like objects that could be used, such as working with worms, or tests that could be performed. Although the use of questions that have personal interests should be encouraged, the teacher needs to ensure that through answering the question students can explore the content objectives of project. This often requires the teacher to use various instructional strategies, such as asking questions, to help focus the students. For instance, in the class working on the project "Where does all our garbage go?" one group of students asked: "When there is water in one [decomposition] bottle and apple juice in another which decomposed faster?" because one of the students like apple juice. Although one student raised concerns about the merit of the question, others rejected her suggestions and were not focusing on the scientific merit of the question. It was not until the teacher conversed with the group about what apple juice might represent in nature, that they realized that the experiment was about acid rain.

Students also used personal experience to generate questions. In a project on water quality one group asked the question: "Does the water in various places around Ann Arbor have fecal coliform? If so, then to what degree?" because one of the students in the group observed professionals testing his pond for fecal coliform. This question allowed students both to conduct investigations to answer the questions and also to explore important content related to the project. However, initially the students did not focus on the scientific merit of the question, teachers needed to support students in seeing the scientific merit of the question. The challenge we face as educators is how to capitalize on the personal experience and interest of students, yet at the same time help the learners explore powerful scientific ideas.

There are several possible explanations for why students generate these types of questions.

One possibility is that students do not have enough experience with inquiry to fashion meaningful questions that are also feasible to carry out. In fact, students may view their task as generating a question which is acceptable to the teacher and which they are able to do in the

classroom rather than as a task of building knowledge. Bereiter (1990) notes that students often do not behave as intentional learners unless prompted consistently. Intentional learners allocate time and effort to identifying problems or questions in a domain, actively seek explanations for those problems via gathering information or conducting investigations, and try to build knowledge rather than just memorize answers. This type of behavior takes time to develop in students.

Some educators might claim that the solution to promote good question asking is to use traditional didactic skill based instruction. However, several studies show that asking good questions comes from having experience asking questions and learning how questions influence the design and conduct of an investigation. The reason is that learning content and inquiry should be closely intertwined rather than separated; like other forms of learning, student ability to generate questions is fostered through active engagement. In fact, Roth and Roychoudhury (1993) reported that over time, as students engaged in experimentation, the questions students used to guide inquiry became more specific and included particular variables and relationships. Scaradamalia and Bereiter (1992) found that the level of questions students posed improved as they explored a topic and gained more background knowledge. Krajcik et al. (1998) showed that students were able to profit from suggestions of the teacher and also use what they had learned previously to improve their questions even early in their introduction to inquiry.

Several strategies have been shown to help students ask more productive questions. Erikson and Lehrer (1998) focus on use of critical standards, which serve as heuristics for question generation. They showed that when critical standards are constructed by the class, there is an emphasis on negotiation among students. Rather than imposing definitions of good questions, the teacher helps students to see that certain questions are less effective than others for promoting knowledge building. For example, teachers might suggest that students should consider the breadth of the question, the ideas that need to be explored, the accuracy with which it reflects what students want to know, and the feasibility of being able to find information.

Erikson and Lehrer showed that over time students developed critical standards that included potential for learning, interest, potential for generating explanations and complex searches. The types of questions students posed changed based on these standards; rather than searching for facts or yes/no answers they required integration of multiple sources of information, categorization and selection of areas in which to search, and the generation of new questions. Moreover, students showed greater understanding and involvement when attempting to answer these questions.

Obviously, to generate worthwhile questions, students must receive timely, informative, and critical feedback from teachers, peers and others. They must also have opportunities to revise their questions and generate new ones. In addition, questions can be evaluated using whole class critique sessions. To support such discussion and student self-assessment concerning questions, teachers can provide skill templates which serve as scaffolds. However, because students are concerned with completing assigned work, they may be hesitant about devoting time to revising their work even when suggestions are offered. In addition, it is possible that students may not understand how feedback can be used for improving their questions. Consequently, teachers must emphasize the importance of revision and allocate time for it.

#### **Gathering Information: Inquiry on the WWW**

Students might seek information to refine or answer a question, to design investigations, or to interpret findings. One increasingly popular source for gathering information is the World Wide Web. Soloway, Krajcik and their colleagues (Wallace, et al., 1998; Hoffman, et al., 1997) have been exploring how students search for and make use of information on the WWW. Congruent with reports of others (Bereiter, 1990), they find that many students do not behave as intentional learners who aim to increase or build knowledge as they search. Instead, students interpret the task of seeking information about a question as one of getting the right answer or good hits. Moreover, students' background knowledge about their question often is limited; as a result they have trouble generating any keywords other than those used in their questions.

Failure to create synonyms may also be due to limited appreciation for the significance of keywords or a lack of understanding about how the technology works.

In addition Wallace, et al., report that students do not have efficient ways to monitor what they have accomplished; they lose their place if the search continues over a period of time, often repeating what they have done before or not making use of the information they have already gathered. Moreover, they have few strategies for reading or evaluating a considerable amount of material on-line. Perhaps it is because students are used to looking up brief answers in textbooks or other reference sources like encyclopedias or dictionaries, they may have neither skills nor inclination to critique what they find (Mergendoller, 1996).

These findings point to some of the areas in which students need support if they are to conduct effective searches, and suggest that a major challenge to using digital information resources is to provide tools which allow students to embed information seeking in a sustained process. Such tools must support both searching for simple answers where students are looking for factual information, and also complex exploration of information when learners are trying to understand a multifaceted problem. Based on classroom observations of students, Artemis was created to support students as they access and use digital information over the WWW (Wallace, Soloway, Krajcik, et al., 1998). Artemis allows students to accomplish multiple tasks within a single computer environment. This helps work from not becoming fragmented and allows them to return to where they left off in prior sessions. The workspace allows for recording of searches and includes links to actual documents, helping students sustain the information seeking process over time.

One feature, the question folders, support students in thinking about and organizing the information they find in terms of their query. They also help students to note what other questions or information they might usefully pursue. Students can store links to items they find interesting in question folders, and can create multiple folders that reflect different areas of the search or the refinements of an initial question. The folders allow flexibility in storing links and are available across multiple work sessions so that students can draw on what they have done

before. Students can add or delete items or evaluate what they have found to date. Also, past results windows keep a live list of student searches so that they can see how they searched previously and what they have found. This feature is helpful, since observations indicate that students forget which queries they have submitted, and consequently repeat the same questions. It also allows students to index what they found and to review their process over time.

There is a broad topics feature which includes a list of topics organized by domain. The topics present a hierarchy of terms which can be browsed or searched as the first step in creating a query. It is intended to help students generate keywords and draw upon prior knowledge as well as giving them a view of the structure of the content area they are exploring and providing them with alternative and productive ways to search.

Artemis is connected to the University of Michigan Digital Library that contains a collection of relevant sites for middle grade students (see http: http://umdl.soe.umich.edu). The objective is to alleviate the frustrating problem students often have of getting numerous irrelevant hits when performing a WWW search. Teachers and students also have the ability to critique, comment and recommend sites. Reading others' recommendations and their accompanying rationales, and contributing their own critiques can help students learn to evaluate information and sites and also increase motivation.

#### **Designing and planning investigations**

Krajcik et al. (1998) found that during their initial experience with designing investigations, middle school students created experimental and descriptive designs, which varied in complexity from using only one variable to comparing several levels of different variables. Small group discussions about designs primarily centered on feasibility and procedures. For instance, many students considered the types of samples to use, ways to create or obtain the samples, and the amount of material needed. They also discussed the need for controls. Some groups, however, had difficulty grasping how to create controlled environments, confounded variables, and misjudged the feasibility of what they were trying to do.

Students' planning for data collection ranged from thoughtful to haphazard. Good plans include measurements related to the question, specifying what students are looking for as they measure or observe, and indicating the number of times measurements will be taken. They also detailed procedures to follow and included a way that data will be tracked and organized. Some planning problems students had were with qualitative techniques that involved drawing or writing a brief statement of what they observed. Generally, groups neither specified what they were looking for and nor how the observations would help in answering their questions. Also, those who planned to use quantitative data often included measures with which they were familiar, like pH, but which were not always appropriate for their purposes.

One reason for students' difficulties may be that they have had little experience devising various techniques to gather or understanding ways to interpret data and draw conclusions. As a result, they are not proficient at eliminating uninformative measures and do not realize the importance of being clear about their purpose. Thus students would benefit from having to explain how the measures selected relate to their questions, and be specific about what particular observations will indicate about the problem under study. Moreover, students need help in creating realistic plans. They sometimes overestimated how much they could accomplish within the time period allocated and ran out of time to complete the complicated set of things they had decided to do.

In addition, although students presented their designs and plans to the class for suggestions, the presentations as well as many of the comments concerned specifics of the procedures rather than their purpose. Templates, which include questions about how the design and measures answer the question and justification for the feasibility of the data collection plans, could be used to guide the content of presentations and also questioning during the presentation. Using such templates, it is also possible to have peers review plans or have students engage in self-assessment of their plans. Allowing time for students to incorporate feedback, revise their plans, and to emphasize the scientific merit of the inquiry is crucial in helping students create better design and plans.

#### **Carrying out investigations**

It is important for students to be thorough, systematic, and precise in collecting and describing data as they conduct investigations. Krajcik et al. (1998) report that many students were careful in setting up experimental procedures and constructing apparatus, following directions precisely. However, students varied considerably in how systemic they were in following through on their plans for collecting and recording data, despite the fact that many were quite careful to create charts to help them track and organize data. Some groups ran out of time because they did not share responsibility for data collection and consequently failed to complete necessary measurements. Others did not collect the measures they had planned but focused on phenomena that attracted their attention, like bad smells or strange looking molds. They did not indicate how these phenomena were related to the scientific issues under study.

These problems illustrate students' need for help in managing complexity and time, and focusing their attention on both the inquiry question and on the immediate needs entailed in collecting data. Students especially had trouble when plans called for numerous observation or complex data collection procedures. One reason is that often students did not specify what they should record when collecting qualitative data or the reason for recording it. Doing both probably would help students focus on what data is important to gather. In addition, when first introduced to inquiry, students may not appreciate the need for consistency in measurement, following through on procedures, or maintaining experimental controls.

One solution for helping students handle complexity is to simplify and specify procedures so that learners can think about content. However, even in more structured laboratory experiments, students tend to concentrate more on coping with procedures than on what they are supposed to learn (Hofstein & Lunetta, 1982). Moreover students need opportunities to think about procedures in order to appreciate the importance of precision and completeness. To provide such experience, sufficient time must be allowed for pupils to do complicated procedures and to complete the observations required by complex designs. Perhaps most challenging is that when students generate questions that are multifaceted, educators need to determine ways to help

students reduce the complexity of the phenomena under investigation so that they can mange the work, while at the same time maintaining the integrity of the science and the authenticity of the problem.

It is also important for teachers to find ways to extend student interest in incidental observations into a desire to understand how such observations reflect scientific concepts under study. Krajcik et al. (1998) reported that students were excited about what they built and frequently asked about each other's work as they carried out investigations. Students occasionally had animated conversations about unexpected changes that attracted their attention and tried to find out more about what they saw, but they rarely pursued the scientific implications of the observations or considered what they might suggest about other related questions or investigations. Surprise and curiosity can be an initial step in heightening interest in the work (Renninger, Hidi, & Krapp, 1992), but are not likely to be sufficient to sustain cognitive engagement in the investigation over a sustained period.

Using microcomputer-based laboratories can reduce complexity of data collection and representation that interfere with students' thinking about conceptual aspects of the inquiry. Students can use probes to monitor the temperature of a pond, to measure the pH of the pond, or to determine how dissolved oxygen varies at different locations in the pond. Although many of these measurements can be done with traditional laboratory equipment, using MBL has a number of advantages. Probes are often time efficient. They are also more reliable instruments. They can display the results both graphically and numerically so that children can more easily interpret the findings. A major advantage is the simultaneous collection and graphing of data (visually and numerically) which contributes to student understanding (Brasell, 1986; Morkos and Tinker, 1987). Another advantage is that probes allow students to do explorations not typically possible in the science classroom. For instance, using a temperature probe, students can continuously track the temperature of a decomposition column. They can answer questions like, "Does the temperature of the column change at night?" or set up an experiment in an aquarium to see if dissolved oxygen changes with amount of light.

### **Analyzing and Interpreting Data**

Students can create different representations of the data, such as charts, graphs or summary tables to look for patterns and to aid in analyzing and interpreting data. Unfortunately, students often focus on data that interests them or that seems to bear out their ideas. Students need support in making use of all the data they obtained to be accurate in interpreting patterns, and in explaining their conclusions based on scientific concepts and scientific reasoning.

Krajcik et al. (1998) noted that despite the fact that students had prepared charts and tables to record and organize their observations, individuals did not draw on these to aid in transforming the data or looking for patterns of results. That is, they did not make graphs of quantitative data or create summary columns of qualitative data to facilitate comparisons across time and conditions even when teachers suggested that they do so. Perhaps because students did not look for patterns, they provided little interpretation of the data in their reports. Instead, they tended to list findings with minimal elaboration, and failed to articulate how they arrived at conclusions or created logical arguments in which data was used to justify conclusions. Nor did they consistently draw upon background information to help interpret their findings. Penner, et al. (1998) also reported that students tended to describe data rather than identify principles that produced the data when attempting to create models. Linn (1992) noted similar tendencies; students using Computers as Learners Partners experienced difficulties using the results of laboratory based experiments to explain everyday experience, and relied instead on intuitive ideas rather than the ideas under study.

One reason for this problem may be that students have had limited experience with these tasks and also may not know how to develop logical arguments to support their claims. Coleman (in press) reported that students judged explanations as scientific if they included information that not everyone knew, or could see with their own eyes, or needed to be discovered rather than looked up in a book. Palinscar, Anderson, & David (1993) have shown that students need considerable assistance in the process of argumentation, and have developed a program to help them systematically consider alternative explanations for phenomena and to provide

justifications for their reasoning. Obviously, teachers need to model how students might go about the process of data analysis and interpretation. Unfortunately, many teachers may not have experience with this phase of inquiry; they are more likely to have dealt with data from highly structured laboratory experiments where the findings are known ahead of time.

Exciting new software tools are now available to support student in interpreting data. Model-It allows students to build models that illustrate qualitative and quantitative relationships among data. In developing models, students specify objects and articulate relationships. As they construct and revise models students examine patterns and trends in data and consider the match between the phenomenon under study and the model they have created. In addition, Data-Viz enables student to link various data types together; for instance pictorial data can be linked to numeric data. Viewing data in these new ways may help enhance student understanding. Evidence from several studies indicates that students can build fairly complicated and accurate models that illustrate deep understanding of science concepts and their relationships (Stratford, Krajcik, & Soloway, 1998; Wisnudel, Stratford, Krajcik and Soloway, 1997).

# **Role of Metacognition in Inquiry**

Metacognition or self-regulation involves planning a course of action, monitoring progress to determine whether goals are being reached efficiently and effectively, and evaluating whether a change in plans or approaches is warranted. To stay organized students must track progress and stay focused on their problem, rather than getting confused or sidetracked by its elements. Doing so requires tactical and strategic metacognition. The first is related to immediate regulation of cognition so that students can monitor their thinking as they work through details of tasks such as who will be responsible for collecting data or using all the data collected in creating models. When exercising strategic control, students think through what might seem to be disconnected elements to organize their efforts in service of the large purpose of the inquiry, such as how the data collection relates to the driving question, what data might be omitted if time runs out, or in what ways the model generated represents an answer to the driving question rather than just a representation of the data. Both types of thinking are needed for students to be

systematic, accurate, and thorough and to make appropriate modifications or to adjust their strategies during inquiry; otherwise investigation runs the danger of becoming more like activity based science were connections among activities and links to the overall issue or question are not evident.

White and Frederiksen (1995) have explored ways to promote metacognition during inquiry. One route is via cognitive facilitation. They argue that developing metacognitive competence requires students to acquire the language to recognize and report on cognitive activities. Thinker Tools Inquiry Curriculum provides this language thorough seeding conversations with categories chosen to represent metacognitive functions such as goal reflection and process reflection.

Examples of language for goals include formulating hypotheses and designing investigations.

Labels are designed to help students recognize, monitor and communicate about cognitive activities like generating multiple options or employing systematic strategies. Each of these can be further broken down into particular strategies and methods that are employed in each stage of the research process. For instance, being systematic means being careful, organized, and logical in planning and conducting work. When problems come up, helping students focus on their thought processes promotes effective decision-making. Students also use these criteria to do reflective assessments in which they evaluate their own and each others' research. White and Frederiksen (1995) have shown that engaging in reflective assessment enhances students understanding of content, of science inquiry, and is especially beneficial for low achievers.

#### The Role of Collaboration in Inquiry

Often, students collaborate as they are engaged in inquiry. Collaboration is a key to help students construct knowledge and to introduce students to disciplinary language, values, and ways of knowing. The aim of collaboration is to build communal knowledge through conversation. Collaboration can occur among a whole class, among groups in a class, and also with people and groups outside the classroom. As students converse, they must articulate their ideas clearly, and consider and draw on the expertise of others (Bruer, 1994). In collaborations

of this sort, groups are not as highly structured as in small group cooperative approaches because the aim is to share ideas with the whole class or community in order to enhance knowledge of all individuals; in contrast to cooperative learning programs, there is little emphasis on assigning roles, group rewards, or group competitions (see Slavin, 1990; Blumenfeld, Marx, Krajcik & Soloway, 1996).

As with cooperative learning, there is considerable evidence that students need support in order to profit from collaboration. Students must manage substantive, procedural and affective matters as they work together. Often they focus attention on the latter two concerns rather than on substantive matters (Anderson, Holland & Palincsar, 1997). Effective collaboration requires students to share ideas, take risks, disagree with and listen to others, and generate and reconcile points of view. These norms do not necessarily pervade classrooms. Attempts to promote positive interactions include instructing for cooperation, including listening and resolving conflicts, and teaching students to appreciate the skills and abilities of others (Webb & Palincsar, 1996). In addition, as discussed above, students do not spontaneously or naturally generate highly efficient questions or explanations on their own and do not productively respond to or evaluate the explanations of others.

One popular approach to facilitating student discussion and comprehension is reciprocal teaching (Palincsar & Brown, 1984; Rosenshine, Meister, & Chapman, 1996). Using a series of questions, like "what is likely to happen next?, what do we know already," teachers model how more expert readers deal with text, eventually releasing responsibility to learners. Coleman (in press) used conversational aids to improve the discussion of ideas and quality of explanations. Students used these prompts during small group sessions as they constructed concept maps. For instance the prompt, "Can you explain this in your own words?", encouraged students to construct explanations. Another prompt, "Can you explain why you think this answer is correct?" encouraged students to justify their responses. "Can you explain this using scientific information learned in class?" encouraged students to draw on background knowledge.

Although students clearly benefited from such supports, it is important to note that the prompts

did not always engender productive discussion; at times no one responded to the prompt, or the discussion went off track, or the discussion did not result in an explanation. Therefore, teachers need to monitor groups carefully even when such conversational aids are employed.

In addition to these approaches, several tools are available to promote collaboration and improve the quality of discourse (Pea & Gomez, 1992; Songer, 1998). For instance, the Computer Supported Intentional Learning Environment (CSILE), developed by Scardamalia and Bereiter (1991) promotes student understanding of subject matter through electronic conversations centered on building a common database. CSILE has been used to support student investigations of topics such as endangered species, fossil fuels, evolution, and human biology. At the beginning of the year CSILE is empty; it is populated by students' contributions of text and graphical notes throughout the year. The electronic database includes four categories of notes or thinking types. These categories correspond to stages in the investigation process. The first two, "what I know" and "high-level questions" are used at the beginning of an investigation as students prepare to research a topic. They then use "plans" to generate a strategy for proceeding, and "new learning" to build a knowledge base. Students' notes as they proceed in gathering information can be in text or graphical form. They can be commented on or added to by other students. The notes are structured to aid student conversation. They include opening phrases like, "One thing I don't understand is..." or "A reference I thought you might find useful is...." The purpose is to assist students in asking further questions, raising counter arguments, suggesting additional sources of information, or offering feedback. Ultimately students write reports that synthesize the results of the class' investigation.

#### **Conclusion**

Inquiry poses challenges for students and teachers. To achieve meaningful understanding of science concepts and processes, students require support though each phase of inquiry.

Supports can come from a variety of sources -- from the teacher, from curriculum materials, from technology, and from peers within and outside the classroom. In almost all cases, the

supports described here are designed to encourage students to be thoughtful as they explore ideas through investigation. Inquiry requires students to exercise tactical and strategic self-regulation. Students need to exercise tactical self-regulation with respect to particulars, such as generating a question or designing an investigation, examining whether the question will actually allow for exploration of the problem at hand or whether the design is adequate for generating useful information. In addition, as they engage in the specifics, students need to keep long term goals in mind and make modifications according to constraints like time and resources, or to discoveries that might result in revision of questions of designs or of data collection procedures. Initially, students will lack experience at being such intentional learners and are likely to need a great deal of assistance to understand how and be willing to think about what they are doing.

Inquiry also poses challenges for teachers. It requires different types of instruction that give equal weight to promoting thinking and teaching content, different management routines as groups of students work on various aspects of phases of inquiry, different ways to promote student interaction and conversation, and different ways to monitor and assess student progress and understanding. It also necessitates different use of time -- for scaffolding, feedback, discussion and sharing, revision, and reflection. Allocating time can be disconcerting for teachers who worry about curriculum coverage. Nevertheless, although teachers find inquiry based instruction difficult at first, they report considerable satisfaction in seeing students motivated to learn, becoming proficient at asking questions and devising ways to answer them, and demonstrating deep understanding of scientific concepts. Sharing experiences and continued exploration of techniques to support students is essential to achieve the recommendation of the National Research Council (1996), that inquiry become a predominant mode of instruction.

#### References

- American Association for the Advancement of Science. (1993). *Benchmarks for science lteracy*. New York, Oxford University Press.
- Anderson, C. W., Holland, J. D., & Palincsar, A. S. (1997). Canonical and sociocultural approaches to research and reform in science education: The story of Juan and his group. *Elementary School Journal*, *97*, 360-383.
- Atwater, M. M. (1994). Research on cultural diversity in the classroom. In D. L. Gabel (Ed.), *Handbook of research on science teaching and learning* (pp. 558-576). New York: MacMillan).
- Audet, R. H., Hickman, P., & Dobrynina, G. (1996). Learning logs: A classroom practice enhancing student sense making. *Journal of Research in Science Teaching*, 33, 205-222.
- Bass, K. M. & Baxter, G. P. (1998) Writing in science...for what purpose? An analysis of notebooks in hands-on science classrooms. Paper presented at the annual meeting of the American Educational Research Association. San Diego, CA.
- Bereiter, C. (1990). Aspects of an educational learning theory. *Review of Educational Research*, 60, 603-624.
- Blumenfeld, P. C., Soloway, E., Mark, R., Krajcik, J., Guzdial, M., & Palincsar, A. (1991). Motivating project-based learning: Sustaining the doing, supporting the learning. *Educational Psychologist*, 26, 369-398.
- Blumenfeld, P.C., & Marx, R.W., Krajcik, J. S., & Soloway, E. (1996). Learning with peers: From small group cooperation to collaborative communities. <u>Educational Researcher.</u> <u>25</u> (<u>8</u>), 37-40.
- Blumenfeld, P. C., Marx, R. W., Patrick, H., & Krajcik, J. S. (1998). Teaching for understanding. In B. J. Biddle, T. L. Good, & I. F. Goodson (Eds.), *International handbook of teachers and teaching* (Vol. 2, pp. 819-878). Dordrecht, The Netherlands: Kluwer.
- Blumenfeld P., Soloway E., Marx R., Krajcik J., Palincsar, M. & A. (1994), Motivating project-based learning: sustaining the doing, supporting the learning, *Educational Psychologist*, 26, 369-398.
- Brown, A.L., & Campione, J.C. (1994). Guided discovery in a community of learners. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 229-270). Cambridge, MA: MIT Press/Bradford Books.
- Britsch, S. J. & Shepardson, D. P. (1997). Children's science journals: tools for teaching, learning and assessing. *Science and Children*, *34*, 12-17.
- Brasell, H. (1987). The effect of real time laboratory graphing on learning graphic representation of distance and velocity. *Journal of Research and Science Teaching*, 24(4), 385-395.
- Bruer, J. (1994). Classroom problems, school culture, and cognitive research. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 273-290). Cambridge, MA: MIT Press.

- Cognition and Technology Group at Vanderbilt (1992). The Jasper series as an example of anchored instruction: Theory, program description, and assessment data. *Educational Psychologist*, 27, 291-315.
- Coleman, E. B. (1998). Using explanatory knowledge during collaborative problem solving in science. *The Journal of the Learning Sciences*, 7(3&4), 387-428.
- Collins, A., Brown, J. S., & Newman, S. G. (1989). Cognitive apprenticeship: Teaching the craft of reading, writing, and mathematics. In L. B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser* (pp. 453-494). Hillsdale, NJ: Erlbaum.
- Edelson, D. (1998). Realising authentic sceince learning through the adaptation of scientific practice. In B. J. Fraser & K. G. Tobin, *International handbook of science education* (pp. 317-331). Dordrecht, The Netherlands:Kluwer.
- Erickson, J., & Lehrer, R. (1998). The evolution of critical standards as students design hypermedia documents. *The Journal of Learning Science*, 7(3&4), 351-386.
- Fensham, P., Gunstone, R., & White, R. (1994). The content of science: A constructivist eapproach to its teaching and learning. London: Falmer Press.
- Hmelo, C. E., & Williams, S. M. (1998). Learning through problem solving [Special issue]. *The Journal of Learning Sciences*, 7(3&4).
- Hyerle, D. (1996). *Visual tools for construcrtive knowledge*. Alexandria, VA: Association for Spervision and Curriculum Development.
- Hoffman, J., & Wallace, R. (1997, March). Structuring on-line curriculum for the science classroom: Design, methodology, and implementation. In E. Soloway (Chair), *Using online digital resources to support sustained inquiry learning in K-12 science*. Symposium conducted at the annual meeting of the American Educational Research Association, Chicago, IL.
- Hofstein, A., & Lunetta, V. N. (1982). The role of the laboratory in science teaching: Neglected aspects of reearch. *Review of Educational Research*, *52*, 201-217.
- Jackson, S., Stratford, S., Krajcik, J., & Soloway, E. (1996). Making system dynamics modeling accessible to pre-college science students. *Interactive Learning Environmments*, 4, 233-257.
- Jackson, S., Krajcik, J., Soloway, E. (1999). Model-It: A Design Retrospective. In Jacobson,M. and Kozma, R (Eds.), Advanced Designs For The Technologies Of Learning:Innovations in Science and Mathematics Education, Erlbaum: Hillsdale, NJ.
- Keys, C. W. (1994). The development of scientific reasoning skills in conjunction with collaborative writing assignments: An Interpretive study of six ninth-grade students. *Journal of Research in Science Teaching. 31*, 1003-1022.
- King, A (1990). Enhancing peer interaction and learning in the classroom through reciprocal questioning (*American Educational Research Journal*, 27, 664-687).
- Krajcik, J. S., Czerniak, C. M., & Berger, C. (1998). *Teaching children science: A project-based approach*. Boston, MA: McGraw-Hill.

- Krajcik, J., Blumenfeld, P., Marx R. W., Bass, K. M., Fredericks, J., & Soloway, E. (1998). Middle school students initial attempts at inquiry in project-based science classrooms. *The Journal of Learning Sciences*, 7(3&4), 313-350.
- Krajcik, J. S., Blumenfeld, P. C., Marx, R. W., & Soloway, E. (1994). A collaborative model for helping teachers learn project-based instruction. *Elementary School Journal*, *94*, 483-497.
- Ladson-Billings, G. (1995). Toward a theory of culturally relevant pedagogy. *American Educational Research Journbal*, *32*, 483-491.
- Linn, M.C. (1998). The impact of technology on science instruction: Historical trends and current opportunities. In D. Tobin, & B.J. Fraser (Eds.), *International handbook of science education* (pp. 265-294). The Netherlands: Kluwer.
- Linn, M. (1992). The computer as learning partner: Can computer tools teach science? In K. Sheingold, L. G. Roberts, & S. M. Malcolm (Eds.), *This year in school science 1991: Technology for teaching and learning* (pp. 31-69). Washington, D. C.: American Association for the Advancement of Science.
- Lunetta, V.N. (1998). The school science laboratory: Historical perspectives and contexts for contemporary teaching. In D. Tobin, & B.J. Fraser (Eds.), *International handbook of science education* (pp. 249-264). The Netherlands: Kluwer.
- McGilly, K. (1994). *Classroom lessons: integrating cognitive theory and classroom practice*. Cambridge, MA: MIT Press.
- Mergendoller, J. R. (1996). Moving from technological possibility to richer student learning: Revitalized infrastructure and reconstructed pedagogy. *Educational Researcher*, 25, 43-46.
- Mark, R. W., Blumenfeld, P. C., Krajcik, J. S., & Soloway, E. (1998). New technologies for teacher professional development. *Teaching and Teacher Education*, *14*, 33-52.
- Metz, K. E. (1995). Reassessment of developmental constraints on children's science instruction. *Review of Educational Research*, 65, 93-128.
- Morkros, J. R. & Tinker, R. F. (1987). The Imapet of microcomputer-based labs on children's ability to interpret graphs. *Journal of Research in Science Teaching*, 24, 369-383.
- National Research Council (1996). *National Science Education Standards*. Washington, DC: National Academy Press.
- Newman, F. M., & Wehlage, G. G. (1993). Standards for authentic instruction. *Educational Leadership*, 50, 8-12.
- Newmann, F. M., & Archibald, D. A. (1992). Aproaches to assessing academic achievement. In H. Berlak, F. M. Newmann, E. Adams, D. A. Archibald, T. Burgess, J. Raven, & T. A. Romberg (Eds)., *Toward a new science of educational testing and assessment* (pp. 71-83). Albany, NY: SUNY Press.
- Novak, J. D., & Gowin, D. B. (1984). *Learning how to learn*. Cambridge, England: Cambridge University Press.

- Palincsar, A., & Brown, A. (1984). Reciprocal teaching of comprehension fostering and comprehension monitoring activities. *Cognition and Instruction*, 1, 117-175.
- Palincsar, A.S., Anderson, C., & David, Y.M. (1993). Pursuing scientific literacy in the middle grades through collaborative problem solving. *The Elementary School Journal*, 93, 643-658.
- Parks, S. & Black, H. (1992). *Organizing thinking: Graphic organizers*. Pacific Grove, CA: Critical Thinking Press and Software.
- Songer, N.B. (1993). Learning science with a child-focused resource: A case study of Kids as Global Scientists. In *Proceedings of the Fifteenth Annual Meeting of the Cognitive Science Society*. Erlbaum: Hillsdale, NJ.
- Penner, D., Lehrer, R., & Schauble, L. (1998). From physical models to biomechanics: A design-based modeling approach. *The Journal of Learning Sciences*, 7(3&4), 429-450.
- Perkins, D. (1992). Smart schools: From training memories to educating minds. New York: Free Press.
- Renninger, K. A., Hidi, S., & Krapp, A. (1992). *The role of interest in learning and developments*. Hillsdale, NJ: Lawerence Erlbaum Associates, Inc.
- Rosenshine, B., Meister, C., & Chapman, S. (1996). Teaching students to generate questions: A review of the intervention studies. *Review of Educational Research*, 66, 181-221.
- Roth, W.M. (1995). Authentic School Science. Netherlands: Kluwer Publishers.
- Roth, W.M., & Roychoudhury, A. (1993). The development of science process skills in authentic contexts. *Journal of Research in Science Teaching*, 30, 127-152.
- Salomon, G., Perkins, D. N., & Globerson, T. (1991). Partners in cognition: Extending human intelligence with intelligent technologies. *Educational Researcher*, 20, 2-9.
- Santa, C. M., & Havens, L.T. (1991) Learning through writing. In C..M. Santa & D.E. Alverman (eds). *Science learning, processes and applications* (pp.122-133) Newark, DE. International Reading Association.
- Scardamelia, M., & Bereiter, C. (1992). Text-based and knowledge-based questioning by children. *Cognition and Instruction*, *9*, 177-199.
- Scardamalia, M., & Bereiter, C. (1991). Higher levels of agency for children in knowledge building: A challenge for the design of new knowledge media. *The Journal of the Learning Sciences*, 1, 37-68.
- Sherwood, R., Petrosino, A., Lin, X. D., and the Cognition and Technology Group at Vanderbilt (1998). Problem based macro contexts in science instruction: Design issues and applications. In B. J. Fraser & K. Tobin (Eds.), *International handbook of science education* (pp. 349-362). Dordrecht, Netherlands: Kluwer.
- Singer, J., Krajcik, J., & Mark, R. (1998). Development of extended inquiry projects: A collaborative partnership with practitioners. Paper presented at the annual meeting of the American Educational Research Association, San Diego, CA.

- Slavin, R. E. (1990). *Cooperative learning: Theory, research, and praftice*. Englewood Cliffs, NJ: Prentice Hall.
- Soloway, E., Guzdial, M., & Hay, K. E. (1994). Learner-centered design: The challenge for human computer interaction in the 21st century. *Interactions*, *1*, 36-48.
- Soloway, E. (1997). Using on-line digital resources to support sustaineed inquiry learning in K-12 science. Symposium presented at the annual meetings of the American Educational Research
- Soloway, E., Krajcik, J., Blumenfeld, P. C., & Marx, R. W. (1996). Technological support for teachers transitioning to project-based science practices. In T. Koschman (Ed.). *CSCL: Theory and practice of an emerging paradigm.* Mahwah, NJ: Erlbaum.
- Soloway, E., & Krajcik, J. S. (1996). The Investigator's Workshop: Supporting authentic science inquiry activities, NSF, 1996-1998.
- Songer, N. B. (1998). Can technology bring students closer to science? In B. J. Fraser and K. G. Tobin, International handbook of science education (pp. 333-347). Dordrecht, Netherlands: Kluwer.
- Spitulnik, M. W., Stratford, S., Krajcik, J., & Soloway, E. (1998). Using technology to support students' artefact construction in science. In B. J. Fraser and K. G. Tobin, *International handbook of heience hducation* (pp. 363-381). Dordrecht, Netherlands: Kluwer.
- Stratford, S. J., Krajcik, J., Soloway, E. (1998). Secondary students' dynamic modeling processes: analyzing, reasoning about, synthesizing, and testing models of stream ecosystems. *Journal of Science Education and Technology*, 7(3), 215-234.
- Wallace, R., Soloway, E., Krajcik, J., Bos, N., Hoffman, J., Hunter, H. E., Kiskis, D., Klann, E., Peters, G., Richardson, D., & Ronen, O. (1998). ARTEMIS: Learner-centered design of an information seeking environment for K-12 education. In *Human Factors in Computing Systems, CHI-98 Conference Proceedings* (pp. 195-202).
- Webb, N. M. & Palincsar, A. S. (1996). Group processes in the classroom. In D. Berliner & R. Calfee (Eds.), *Handbook of research in educational psychology* (pp. 841-873). New York: Simon & Schuster.
- White, B. Y., & Frederiksen, J. R. (1995). *The ThinkerTools inquiry project: Making scientific inquiry accessible to students and teachers*. (Causal Models Research Group Report No. 95-02). Berkeley: University of California, School of Education.
- White, R. & Gunstone, R. (1992). Probing Understanding. London: Farmer Press.