Designing curriculum to meet national standards

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Science education standards advanced by the American Association for the Advancement of Science (1993) and the National Research Council (1996) urge less emphasis on memorizing decontextualized scientific facts and more emphasis on students investigating the everyday world and developing deep understanding from their inquiries. 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, 1996, p. 23). By emphasizing scientific inquiry, the standards challenge the education and science communities to transform the very heart of students’ experiences in science classrooms. In support of the standards, new approaches to science instruction feature inquiry as essential for student learning (Krajcik et. al., 1998; Lunetta, 1998; Roth, 1995). These approaches assume that the students need to find solutions to real problems by asking and refining questions (Bereiter & Scardamalia, 1989), designing and conducting investigations (Schauble, Glaser, Duschl, Schulze, and John, 1995), gathering and analyzing information and data (Vellom & Anderson, 1999; Hancock, Kaput, & Goldsmih, 1992), making interpretations, drawing conclusions (Chinn and Brewer, 1993), and reporting findings.

The spirit of the science education standards represents a dramatic shift in what and how science is taught in k-12 classrooms. In order to enable teachers to accomplish the ambitious agenda advocated by AAAS and NRC, educational researchers and professional educators need to create a research and development program to support reform (Marx, et al., 1998). Such an agenda needs to address the full range of issues associated with reform: curriculum and pedagogy, management and policy, teacher professional development, new learning technologies, and community engagement. By studying the intersection of these issues and developing programs of research-based practice around them, partnerships of researchers and educators can begin to create the know how to help teachers meet the new standards (Blumenfeld, in press).

In this paper we report our work on one of these issues—curriculum materials to support reform. Researchers at the University of Michigan have been working together with the Detroit Public Schools to reform science education for middle schools. The collaborative work between DPS and UM takes place within two projects funded by the National Science Foundation--the Detroit Urban Systemic Program and the Center for Learning Technologies in Urban Schools (LeTUS), which takes as its core challenge the infusion of technology to support learning into urban classrooms. We are documenting situations that influence technology acquisition, exploring how technology can be embedded in science curricula, identifying problems that present barriers to success, and finding local solutions to these problems.

When we began this collaborative effort, we found that a major challenge for imbedding technology use in urban schools was the lack of curriculum materials that match science content with the appropriate use of learning technologies. To meet this challenge it became necessary to develop materials that simultaneously are suitable for use in schools that serve diverse populations, promote inquiry, are based in research on thinking and learning, and make extensive use of learning technologies as the vehicle for students to develop deep understanding of scientific concepts and processes.

Our approach to developing curriculum materials entails collaboration among teachers, school and district administrators, university scientists, educational researchers, and curriculum specialists (Krajcik, et al., 1994; Singer, et al., 1998). Through this process we have developed, enacted, and revised several curriculum projects. Our development process is based on design principles that are derived from theoretical and empirical literature on teaching and learning and the literature on science education standards. In this article we describe these curriculum design principles, grounding them in a social constructivist perspective, and provide examples of how the principles become manifest as curricular activities.

Assumptions for Designing Curriculum Materials

The assumptions that provide the foundation of our curriculum design principles are derived from a social constructivist perspective (Blumenfeld et al., 1997). Social constructivism is an approach to learning in which students learn concepts or construct meaning about ideas through their interactions with and interpretations of their world, including essential interactions with others (Lave & Wenger, 1991). Four salient features are fundamental to this theoretical perspective: 1) active construction, 2) situated cognition, 3) community, and 4) discourse.

When students are provided opportunities to *actively construct* their understanding of a discipline, deep understanding is more likely to develop (Krajcik et al., 1998; Roth, 1994; Tinker, 1994). Perkins (1993, 1994a, 1994b) argues that engaging students in performance provides opportunities that promote deep understanding. This performance perspective suggests that students construct knowledge by engaging in learning environments that require them "to explain, muster evidence, find examples, generalize, apply concepts, analogize, (and) represent in a new way."(Perkins, 1993, p. 29). Actively constructing knowledge or engaging in a performance of understanding requires that learners become immersed within the context of the discipline (Perkins, 1993,; Roth 1994). Such disciplinary contexts provide *situations* within which novices can learn through increasingly autonomous activity in the presence of social and intellectual support. Lave and Wenger (1991) argue that abstract and generalized knowledge gains its power through the expert's ability to apply it in specific situations. Hence, in order to deeply understand the principles of a discipline, students must actively see how knowledge or skills function within the context of the discipline.

Socialization into the culture of a discipline is promoted by extensive and repeated exposure to the *community* of practitioners in the discipline (Perkins, 1993). Communities of practice in disciplines share a culture and like all cultures, members have developed tools for conducting activities and regulating interactions of the community. Learners appropriate many cultural tools, ranging from the meanings of words, to methods of identifying and solving problems, and even to the epistemologies of formal disciplines. By being immersed in the culture of a community of practice (e.g. science, math, history), students learn ways of knowing in the discipline, what counts as evidence, and how ideas are substantiated and shared.

Participation within a community requires the use of language to exchange and negotiate meaning of ideas among its members. Learners are introduced into the language community by more competent others and appropriate the symbolic forms of others and the functionality of those forms through language. While the intrapsychic functions of language enable the learner to construct understanding, the interpersonal functions allow the learner to engage in *discourse*. Hence, the learner becomes a member of a discourse community. The movement between the interpersonal and intrapsychic uses of language constitutes one of the essential sites of learning.

From this perspective on social constructivism, we have developed an approach to teaching and learning--project-based science—that engages students in curricular units (we call them "projects") that last from 4-10 weeks. These project encompass science content that relates to national science education standards and local school district curriculum frameworks. This approach to learning through inquiry embeds the pervasive use of technologies in collaborative classroom settings (Marx et al. 1997).

Curriculum Design Principles

We have derived seven curriculum design principles from our conception of social constructivism and other important components of curriculum development, including a consideration of stakeholders and national policy bodies such as NRC and AAAS. These principles provide a foundation for the design of inquiry curriculum projects. Table 1 presents the seven design principles we have been using. Curriculum materials created by using these principles can promote understanding of scientific concepts and inquiry strategies and address the needs of diverse students (Krajcik et al., 1998, Krajcik et al., 2000, Singer et al. 1998).

Table 1.

Curriculum Design Principles

Design Principle	Description	Instructional Component
Context	Meaningful, defined problem space that provides intellectual challenge for the learner	· Driving Questions · Sub-Questions · Anchoring Events
Standards based	Publication by larger community experts that defines the language and methods of the larger community	· AAAS –Benchmarks · NRC–National Standards · Benchmark lessons
Inquiry	The accepted method of the scientific community for solving problems. It is a set of interrelated processes by which scientists and students pose questions about the natural world and investigate phenomena (NRC, 1996 , p. 214)	· Asking Questions · Data collection, Organization and Analysis · Sharing and Communicating data
Collaboration	Interaction students, teachers, and community members to share information and negotiate meaning	· Small group design meetings · Think, pair, share learning strategy · Group presentations
Learning Tools	Tools that support students in intellectually challenging tasks	· Data Collection · Communication · Modeling
Artifacts	Representations of ideas or concepts that can be shared, critiqued, and revised to enhance learning.	· Concept maps · Scientific models · Lab reports
Scaffolds	A series of methods which fade	· Learner centered

	over time to control learning activities that are beyond the novices’ capabilities so that they can focus on and master those features of the task that they can grasp quickly (Schunk, 2000)	design · Teaching strategies · POE: Predict, Observe, Explain · Driving Question Board

Context

The contexts for curriculum projects are created through the use of driving questions. Driving questions serve to organize and guide instructional tasks (Krajcik, Czerniak, & Berger, 1999; Krajcik et al. 1998), thereby situating learning for students. The driving question uses students’ real world experiences to contextualize scientific ideas and subquestions and anchoring events to help students apply their emerging scientific understandings to the real world, thus helping them see value in their academic work.

Driving questions help engage students in the culture of a scientific community. The source of the questions being asked and investigated is an important feature of the curriculum design process. The driving question is initially developed based upon its potential meaning for students, which is determined through repeated conversations with teachers, community members, and content experts. The learning environments designed to help students answer the driving question immerse them in a scientific culture, including practices such as debating ideas, designing and conducting investigations, reasoning logically, using evidence to support claims, and proposing interpretations of findings.

Driving questions tend to be broad and open-ended; they need to have this character in order for them to be authentic and encompass worthwhile science content. Because of this open-endedness, however, students have difficulty recognizing what science principles are relevant and necessary in order to construct a meaningful response to the driving question. Methods for facilitating students through these difficulties are addressed through the use of related subquestions and anchoring events that help students link learning activities back to the driving question.

Our projects are relatively long term because they involve answers to complex questions. Questions that middle school students find engaging, such as "What is the quality of water in my river?" "Why do I need to wear a helmet when I ride my bike?" and "Can my friends make me sick?" can involve substantial science In order to link the science to the driving question, students need to learn many related concepts, processes, and skills that a novice may not recognize as being directly related to the driving question. For instance, we know that experts have well-developed knowledge in their domain of expertise (Chi, Glaser, & Farr, 1988) that they notice patterns novices fail to see (Lesgold et al., 1988), have fundamentaly different problem solving strategies (Dunbar, 1995) and have different ways of representing information (Chi et al., 1981). Assisting in the developmental transformation from novice to expertise is a fundamental component of how we come to learn (Bransford, Chickering, and Brown, 1999). By using subquestions and insuring that the students understand the relations among the driving question and its subquestions, we can help students keep the driving question in mind throughout the project. Careful construction of the questions allows them to be cumulative over the project and help learners construct a greater understanding of the scope and depth of the driving question.

Contextualization is also supported by the creation of anchoring events that enable students to visualize how the project's substance relates to their community, family, or themselves. Anchoring events (Cognition and Technology Group at Vanderbilt, 1992, help render abstract ideas more concrete and thus provide a cognitive mooring around which newly learned ideas can be linked with prior understandings. Ideally, anchoring events directly engage learners with the scientific phenomena that are addressed by the driving question. Projects that address environmental themes are particularly well suited for the creation of anchors that engage students directly with phenomena. For the driving question "What affects the quality of air in my community?" students can walk around their school and the immediately surrounding community making observations and taking pictures that demonstrate their questions about how air quality might be affecting their environment. The pictures can be displayed around the room and viewed throughout the project to anchor learning in the students' personal experience.

Projects also allow students opportunities to ask their own questions related to the driving question. For instance, when students return from their walk, they can collaboratively generate questions related to the driving question. Student questions are posted on the driving question board to serve as a reminder throughout the project. Students often find answers to their questions as a result of project activities. Asking their own questions allow students to gain ownership of project, fostering sustained student engagement.

Standards based

The second curriculum design principle is associated with all four social constructivist features. National standards (Rutherford & Ahlgren, 1990; AAAS, 1993; NRC, 1996) were crafted by a broad coalition of organizations and leaders in the scientific and educational communities. These documents provide frameworks for curriculum to communicate the language of the disciplines and engage learners in the nature of science and practices of the scientific community. The AAAS and NRC documents contain chapters that specify the sequence and substance of science concepts, specialized language, and practices and methods for asking questions and solving problems.

In addition to communicating the language, tools, and approaches of the scientific community, national standards also make claims about how to help learners understand the nature of science, advocating a pedagogical approach that promotes the active construction of knowledge. For example, the NRC (1996, p. 29) suggests that “in the same way that scientists develop their knowledge and understanding as they seek answers to questions about the natural world, students develop an understanding of the natural world when they are actively engaged in scientific inquiry – alone and with others.” Moreover, the standards promote a pedagogical approach emphasizing that learning should be situated in the life of the child.

In addition to the driving question situating the project in the lives of learners, it also must facilitate the learning of worthwhile science concepts. Once a driving question is framed, it is assessed based upon the potential concepts and processes that are needed to develop a knowledgeable response. These concepts and processes are then compared against the local, state and national curriculum standards. To meet curriculum standards and help students develop deep understanding of content, benchmark lessons are employed. Benchmark lessons help students learn difficult concepts, illustrate important laboratory techniques, or develop investigation strategies (Hunt & Minstrell, 1994). Benchmark lessons can also be used to model thinking or stimulate curiosity. A wide variety of student-centered teaching strategies can be used to construct benchmark lessons (Krajcik, et al., 1999).

Inquiry

Sustained inquiry is the accepted norm in the scientific community for solving problems; it is the extended engagement in this process that facilitates students’ immersion in a scientific community (NRC, 1996; Perkins, 1993). Extended inquiry also provides a mechanism to facilitate discourse. As students collect, analyze and share information they must negotiate the meaning of data. By engaging in sustained investigations, students learn scientific processes and how these processes work together to generate new information. Inquiry allows students to experience a range of scientific phenomena as they make observations and manipulate variables to see how phenomena change under different conditions. Investigations provide opportunities for students to design experiments thereby using ideas related to independent, dependent and control variables. Investigations also allow students to analyze data and support conclusions using evidence. More competent community members (e.g. teachers, scientists, health professionals) may provide guidance and insight during the planing, conducting, or analysis portions of an investigation. Care must be taken, however, when utilizing outside experts that the experts are cognizant of the special needs of young learners (Petrosino, 1996). How tight an investigation is scaffolded is determined by several factors including the complexity of the concepts, difficulty of the measuring techniques or technologies, students' familiarity with the inquiry process, and the teacher's understanding of the science being investigated.

<u>Collaboration and Student Discourse</u>

Projects are designed to foster student collaboration within a learning community. Students communicate with each other, teachers, community members, and scientists to find information and solutions to their questions and to discuss their findings and understandings. Projects are designed to extend student learning experiences beyond the classroom by posing driving questions that situate the science with issues that are likely to be of interest to scientists, community based organizations, and families. Collaboration during investigations and benchmark lessons may involve students interacting with peers in small groups or as part of large class discussions, or students may interact with more knowledgeable community members.

The collaboration principle is difficult to enact in classrooms. Science involves very active collaboration among participants that is hard to emulate in the physical space, time schedules, and norms of interaction in schools (e.g., classrooms should be orderly and quiet). In a very real sense, the collaboration principle in inquiry violates what Tyack and Cuban (1995) call the grammar of schooling—all of those taken-for-granted practices that in the aggregate constitute "real school." Moreover, the discourse elements of collaboration require a range of teacher understanding that is very challenging. The discourses of formal science disciplines represent the knowledge and the ways of knowing of the disciplines. Many teachers are not nor have they ever been actual practitioners of the science disciplines that they are asked to teach. For example, they might find it difficult to formulate researchable questions, design controlled investigations to examine those questions, represent data in various ways, or interpret findings in the face of conflicting or variable data. In a word, they may not be fluent in the discourse practices they are being asked to introduce to students. Problems such as these require careful attention in the design of the collaboration activities so that both teachers and students can engage them productively.

Learning Tools

The integration of learning technologies, new computer and telecommunications based tools that support students in intellectually challenging tasks, embodies all four social constructivist features. Our projects are designed to incorporate learning technologies that are appropriate for formulating answers to the driving question. The nature of the problem being solved and the accepted methodologies of the scientific community dictate the tools utilized in various projects.

Inquiry can be done in classrooms without learning technologies, but learning technologies expand the range of questions that can be investigated, data that can be collected, representations that can be displayed to aid interpretation, and products that can be created to demonstrate understanding (Scardamlia & Bereiter, 1996; Edelson, Gordin, and Pea. 1999). These technologies help students and teachers communicate (Levin, 1992; Pea, Edelson, & Gomez, 1994), explore phenomena (Linn, 1996), find information (Wallace, Kupperman, Krajcik, & Soloway 2000), conduct investigations (Rubin, 1993), build models that provide explanations of phenomena (Jackson, Krajcik & Soloway, 1996), and develop products and communicate with others (Fishman, 1996).

Learning technologies used in our projects mirror those used by scientists in the work place, but designed with learners in mind. The conceptual model used to develop these tools is learner centered design (Soloway et al., 1996; Quintana et al.,, 1999). This approach to the development of learning tools addresses technology issues that are unique to learners, including the design and deployment of scaffolds in software that are sensitive to when they are needed, fade when students no longer need help, and support complex processes that learners are not capable of completing without assistance (e.g., cueing metacognition or prompting learning strategy use). In addition, learner centered design suggests that tools should be broadly applicable in a range of projects and have commonalties in the user interface to reduce the amount of learning needed to use the tools.

Artifacts

As students conduct investigations and engage in benchmark lessons, they create artifacts that can be shared, critiqued, and revised to further enhance understanding and serve as the basis for both formative and summative assessment (Minstrell, 1989). The parameters for the creation of artifacts are partially dictated by the context established by the driving question or related subquestions. Artifacts may also be constrained by the need to mirror representations of products constructed by community experts (e.g., simulations, models, and publication of data). As artifacts are constructed and critiqued they foster discourse within the classroom. Students may be required to explain how their artifact is related to the driving question or subquestion or represents a specific concept. By promoting public sharing, critiquing and revision of artifacts, active construction of student understanding is fostered.

Artifacts may be ongoing and allow for iterative points of assessment of students' emerging understanding of content, process, and the driving question. In addition, artifacts also serve to bring closure to the curriculum project in the form of a final product and presentation (Perkins, 1993). Artifacts used as final products allow students to demonstrate the full scope of the knowledge and skills they constructed during the course of the project (Brown and Campione, 1996).

Scaffolds Between and Within Projects

The use of scaffolds to support student learning is strongly linked to the community of learner and discourse features of social constructivism. A fundamental notion is that the assistance of more competent others can be used to help learners accomplish more difficult tasks than they otherwise are capable of completing on their own. There is a hypothetical space between assisted and unassisted performance that Vygotsky (1978) identified as the *zone of proximal development* (ZPD). By identifying a learner's ZPD, a teacher can locate the psychological space in which assistance can help to propel the learner to higher levels of understanding. Because learners construct their understanding, the assistance provided in the ZPD has become known as scaffolding

Projects are designed to guide learning as students are introduced to challenging science concepts and processes. The teacher, learning materials, and technology each provide scaffolds within a project. Teachers model, coach, present benchmark lessons and give feedback. Learning materials scaffold students by reducing complexity, highlighting concepts or inquiry strategies, and fostering metacognition. Technology scaffolds students by providing multiple representations, unveiling additional complexities as the needs of the learner grows, and ordering and guiding processes (such as planning, building, and evaluating). Projects are also designed to support students by sequencing inquiry process and scientific concepts. Learning materials and benchmark lessons are chosen to illustrate particular strategies and the usefulness of technologies. The emphasis is on modeling skills and heuristics, such as how to create tables to keep track of data or how to transform data. This tight structuring affords students the opportunity to experience all phases of inquiry and to build a scheme of how phases of inquiry interrelate. Later, students are given more responsibilities for designing and conducting investigations. Projects are sequenced in order to revisit concepts and because the projects incorporate learning goals illustrated by local, state and national standards, these concepts are reinforced, helping students develop understanding that reflects the complexity of scientific knowledge.

Summary

Table 2 summarizes the relationships among the seven design principles, the social constructivist features described earlier, and the rationales that unite the principles and features. In the next section, we present an example of how this framework can be used to develop materials for middle a school, project-based science curriculum.

An Example Project: "What Affects the Quality of Air in My Community?"

During the four academic school years from 1996 – 2000 the collaborative curriculum design effort of Detroit Public Schools and the Center for Learning Technologies in Urban Schools has developed and piloted six extended inquiry projects. These projects have focused on a wide range of concepts that include: a) physical science (force and motion), b) chemistry (particulate nature of matter, chemical changes, and physical changes), c) geology (hydrology, erosion, and deposition), and d) biology (cells, microorganisms, immunity, and respiration). These curriculum projects were created by applying the seven design principles described above.

Table 2.

Summary of the Use of Design Principles in Curriculum Materials

Design Principle	Social Constructivist Tenet	Rationale
Context		
	Situated	· Driving question and sub-question provide meaningful, specific space for student engagement.
	Community	· Scientific culture determines the manner that questions are framed and the manner in which they are investigated
	Active Construction	· Sub-questions and anchoring events focus students on relationships between newly constructed concepts and ideas
Standards		
	Situated	· Provides framework for the specific strategies for framing and solving problems
	Community	· Developed by larger scientific community for means of enculturating novices into the nature of science
	Active Construction	· Methodological approach advocated by the publication
	Discourse	· Provides framework for the specialized language of the community
Inquiry		
	Community	· The accepted approach by the scientific community for solving problems
	Active Construction	· Extended inquiry engages students directly with the phenomena and supports the learning of key scientific concepts.
Collaboration		

Community	·	An essential part of a community is interaction among its members to share information and reach consensus decisions
Active Construction		
	·	Collaboration among peers and knowledgeable experts necessitates the need for specialized language

Table 2.

Summary of the Use of Design Principles in Curriculum Materials

Design Principle	Social Constructivist Tenet	Rationale
Tools		
	Situated	· The nature of the situation defined by the driving questions constrains the appropriateness of the tools utilized.
	Community	· Tools used mirror the tools utilized by members of the scientific community.
	Active Construction	· Tools are developed and utilized that engage learners in intellectually challenging tasks and that scaffold their needs.
	Discourse	· Learning tools can foster communication among and between local and extended community members
Artifacts		
	Situated	· Parameters for the creation of artifacts is dictated by the context established by the driving question or related sub-question.
	Community	· Artifacts mirror representations of products constructed by community experts
	Active Construction	· When artifacts are constructed and critiqued they foster discourse within the classroom.
	Discourse	· Public sharing, critiquing and revision of artifacts, fosters the active construction of student understanding.
Scaffolds		
	Situated	· Use of sub-questions allows key concepts and processes to be made explicit.
	Community	· Learners assisted by more competent members facilitates learning - Zone of proximal development (ZPD)

Active Construction	·	Learner centered design of technology, provides multiple representations, hides complexities and sequencing processes.

Presented below is an example project illustrating how the design principles are manifested in an curriculum project, “What affects the quality of air in my community?” Table 3 provides an overview of this example project. The “Time” and “Sub-questions and associated content” columns depict how the project unfolds over time. In addition to illustrating the progression of the project, the far right column of the table (“Instructional component”) describes how the design principles are evinced within the project.

<u>Context</u>

The context for this curriculum project relates chemistry content to a problem of substantial interest to urban communities. We arrived at this question by meeting with school district officials to determine content and community members to ascertain issues they found problematic. Parents and other members of the Detroit community described noxious smells in the air and other evidence of air quality that enabled us to develop the driving question “What affects the quality of air in my community?” The project is organized around four sub-questions (Table 3) developed to insure that the curriculum materials address science content associated with the arrangement of particles in air, the chemical structure of air pollutants, and the processes involved in the formation of air pollutants.

The first sub-question of this project is “What are the visible signs of air quality?” This sub-question focuses students on sources and effects of air pollution identified in their local community. To explore this question, students walk around their school and homes identifying potential sources and effects of air pollution. This walk, its subsequent class discussion, and emergent artifacts (observations and questions) constitute the

Table 3.

Overview of the curriculum project “What affects the quality of air in my community?”

Time	Sub-questions and associated content	Instructional component
Week 1	What are the visible signs of air quality? · Sources and effects of air pollution · Introduction of driving question	· Sub-question · Anchoring event · Asking Questions
Weeks 2 - 3	So, What is air, anyway? · Atoms, molecules, compounds · States of matter	· Driving Question Board · Small group and whole class sharing · Benchmark lessons · Modeling of compounds (e-chem). · Pre/Post representations of composition and arrangement of particles in air
Weeks 4 - 6	How are the pollutants formed? · Phase changes · Indicators of chemical changes · Chemical reactions · Conservation of matter	· Driving Question Board · Data collection, manipulation, organization, and analysis · Small group and whole class sharing · Presentations with reflections and critiques · Benchmark lessons · Modeling of sources and effects of air pollution

Weeks 7 – 8	How does our air measure up? · Sources and effects of air pollution · Atoms, molecules, compounds · States of matter · Chemical reactions	· Data collection, manipulation, organization, and analysis · Comparison and analysis of air quality data from multiple large urban centers – (Tool Soup) · Small group and whole class sharing · Final Presentations with reflections and critiques

project's first anchoring event. The walk serves as an anchoring event by providing opportunities for students to link their learning to their experience. The observations recorded and questions raised during this walk are revisited throughout the course of the project. This event also provides the opportunity for the teacher to introduce an essential project support, the driving question board (DQB).

Standards

One of the curriculum goals for this inquiry project is that students should understand the nature of air (e.g., air is a gas, a mixture of many small particles, and composed mostly of nitrogen and oxygen). These ideas are inherent in several middle school objectives (Structure and Matter 4D, numbers 1, 2, and 7) described in AAAS Benchmarks. Through the use of the DQB the teacher can facilitate connections between the driving question, sub-questions, and concepts needed to address the relevant ideas. In addition to sub-questions and the DQB, teachers employ benchmark lessons that support students' understanding of specific concepts, skills, or processes. During the exploration of the sub-questions "So, what is air, anyway?" and "How are the pollutants formed?" the teacher uses strategies in benchmark lessons, such as POE--Predict, Observe, Explain KWL--Know, Want to Know, Learned , whole class and small group discussions, and teacher demonstrations. For the first sub-question, students use a body kinesthetic (Gardner, 1987) strategy by constructing human models of the arrangement and motion of particles within a solid, liquid, and gas. This strategy is also used in benchmark lessons that address the chemical structure of the six criteria air pollutants and the other compounds found in air. During this second body kinesthetic activity students develop human models of "clean" and polluted air.

Inquiry

Exploration of the sub-question "How are the pollutants formed?" begins with students collecting and analyzing exhaust from different types of vehicles. The investigation focuses on the question "Do all cars pollute the same?" The experiment provides students an opportunity to use several scientific processes. Students identify variables that might affect exhaust (e.g. number of miles on the odometer, size of engine, percent octane used as fuel, time since last oil change), collect data for these variables, organize the data in charts and tables, and perform simple analyses of the data (e.g., drawing graphs). In addition to the car exhaust experiment, students collect and analyze data from state and national agencies that monitor levels of the criterion air pollutants.

During this exploration the students explore how the pollutant levels have changed during a five year period and determine patterns for the pollutant levels.

Learning Tools

The students' analysis and interpretation is supported by three related learning technologies --Tool Soup (Quintana et al., 1999), Model-Builder (Jackson et al., 1996) and e-chem. Tool Soup includes databases and a data-visualization tool. A database containing air pollution data for 10 large urban centers from around the United States is explored and analyzed by the students. Files contained in these databases were originally obtained from national and state air monitoring stations. Tool Soup helps students compare the presence of air pollutants at different locations and examine changes in the levels of these pollutants over time. By using a graphical interface, students can isolate these variables, make comparisons, and explore hypotheses about the causes and effects of these pollutants in different locations. For example, students analyze air quality data from two large urban centers: their local community and another region of the United States. In conjunction with their understanding of the National Ambient Air Quality Standards (NAAQS), students use Tool Soup to compare the two locations. Tool Soup supports comparison by providing multiple representations of the selected data, thereby helping learners focus on data analysis and not just the construction of graphs. Differences in pollutant emissions are identified and newly acquired scientific concepts concerning changes in matter are applied to explain them.

Model-Builder helps students make qualitative models of cause and effect relationships. When using Model-Builder, learners create objects ("things" in the system being modeled) with which they associate measurable, variable quantities called factors. Students then define relationships among factors to show how they affect each other. Relationships can model immediate effects or effects over time. The application provides facilities for testing a model and a "Factor Map" for visualizing it as a whole. Students define objects, factors, and relationships among the qualities of factors. For example, in building a model of air quality, air and vehicles represent objects. Factors of vehicles could include the amount of exhaust released and the number of cars in the community. Factors of air could include amount of carbon monoxide and a general quality rating. A relationship could be expressed qualitatively: As the amount of car exhaust increases, the amount of carbon monoxide in the air increases. After a model is built, students can test it to verify that their conjectures are correct. The application enables smooth transitions between building and testing. Closely linking design and testing allows students to make connections between the configuration of relationships they included in their model and the resulting representation of the model's behavior as shown on meters and graphs.

The program e-chem is a visualization tool that allows students to easily construct and rotate 3-dimensional representations of molecules. During the air quality project, students construct representations of molecules found in air (e.g. nitrogen gas, oxygen gas, water, carbon monoxide). These models are first constructed using colored gum drops and toothpicks, which is limited because this activity does not illustrate proper arrangements or multiple bonds. The use of e-chem helps students create more scientifically acceptable representations. For example, the acceptable representation of the diatomic gasses nitrogen and oxygen require the use of a multiple bonds between the atoms. This aspect of molecular models is supported in the use of e-chem but not with the use of gum drops and toothpicks. Students re-construct the same air molecules using e-chem and discuss the difference between the representations.

Artifacts

At the beginning of the exploration into the sub-question "So, what is air, anyway?" students create a picture that represents their understanding of the particulate composition of "clean and polluted" air. This artifact is revisited, allowing for iterative assessment of the students' emerging understanding. After subsequent benchmark lessons illustrating the arrangement and motion of particles, chemical composition of air (an experiment in which students calculate the percentage of oxygen in air), and construction of molecules found in air (using the toothpick and gum drop and e-chem models described above), students reflect on and reconstruct their pictures.

These pre and post air pictures serve as artifacts that assess the students' changing understanding of the particulate nature of matter and as metacognitive aids for students to reflect upon how their understanding of chemical composition and the arrangement of particles in air have changed. Students compare their initial and final pictures and create a written reflection that addresses how the pictures have changed, an explanation for why one version is more scientifically acceptable, and how this knowledge relates to the driving question

The project culminates with the construction of a response to the driving question. Students construct a final artifact, which is a group presentation requiring students to use their knowledge of ideas and processes associated with air pollutants. The knowledge students apply includes comparison of air quality data between different geographical areas, sources and effects of air pollution, chemical composition of air and air pollutants, and chemical formation.

Collaboration

Projects are designed to foster collaboration. This design feature permeates all aspects of the project and is difficult to separate from the investigations, artifact constructions, and benchmark lessons that constitute the project. One primary strategy for fostering collaboration is the extensive use of small and large group discussions. For example when introducing the sub-question “How are the pollutants formed?”, a class discussion is used to review questions, information, and artifacts posted on the DQB. Explicit connections made during this discussion include the pollutant sources read or seen during the school walk and the differences in chemical composition of clean and polluted air. Through this discussion students determine that vehicles are a major source of pollution that were observed during their community walk. This finding leads the students to an investigation testing automobile exhaust. The investigation ends with teams of students developing and presenting their experimental results and conclusions.

Another strategy engages students in small group collaborative work in order to conduct their investigations. For example, when examining factors that cause the amount of pollutants in exhaust to differ among cars, students identify, plan, and conduct experiments in small collaborative groups. The groups plan the experiment by brainstorming potential factors, evaluating the merits of each factor based upon known criteria, and developing research questions and hypotheses. During this collaborative exercise students must reach consensus on the factor they are going to investigate and provide the class with a rationale for why they selected the factor.

The final artifact is a performance in which small groups of students present a comparison of air pollution levels between their local area and the selected city and describe the chemical composition of pollutants, chemical formation of pollutants, and sources and effects of pollutants. All students are expected to participate actively and to incorporate multimedia or visual representations of data.

Scaffolds

Middle school students have difficulties with several aspects of inquiry including asking questions, making decisions concerning how best to proceed within an extended inquiry, and understanding how information, concepts, and smaller investigations relate to the driving question (Krajcik et. al, 1998). The driving question board is a support structure that assists in these cognitively demanding tasks. The DQB provides a public location where the class can identify what they know, what they need to know, and what they have learned. Students and teacher can use this space to explicitly relate concepts to the driving question, discuss the state and future direction of the inquiry, and share and negotiate the meaning of experiments and information relevant to the driving question. The teacher adds information to the DQB continuously during the project. All of the subquestions are put on the board, decisions about how to conduct investigations are posted, as are examples of data and representations of data. Moreover, in order to demonstrate the importance of interpretation, conjectures that the students raise about possible meaning of data are posted.

Inquiry is not the only aspect of the project that requires scaffolds. Collaboration, using learning technologies, and developing quality artifacts all need to be scaffolded. Prior to the construction of the project’s final artifact, students are provided with a rubric and checklist of the key components. Students then watch a video tape of presentations from previous years in order to view and discuss the merits of a quality product. At the completion of each presentation segment, the students complete a rubric and discuss the strengths and weaknesses of the presentation. In addition to the use of rubrics and past presentations, students are provided with checklists to help them organize their group work and as a means for the teacher to assess progress.

Constructing, simulating, verifying and validating models pose a serious challenge for students (Mandinach & Cline, 1989; 1994). Current procedures for teaching modeling are complex, requiring considerable prior knowledge and mathematical ability on the part of students. To scaffold novices in the challenges associated with creating dynamic models, we use the computer application, Model-Builder, which requires minimal prior knowledge from other domains.

In order to help students construct their initial models, the teacher engages them in a series of specifically scaffolded learning events. The first of these experiences introduces students to the content to be modeled. This content is derived from contextualizing events (e.g. school walk and car exhaust experiment) that focus students on potential sources and effects of air pollution. Next, the teacher guides the students through transitioning tasks that conclude with introducing students to the new learning technology. In the transitioning tasks students draw pictures of 6 - 7 objects that either cause or are affected by air pollution. Small group and whole class discussions follow that focus students on their pictures, as the teacher helps the class reach a consensus about the objects they will include in their model. The class then constructs a representative class picture. This careful scaffolding helps the students understand that the model they create in Model-Builder is a representation of the actual phenomena that they have observed. Later, as the students develop more facility in computer modeling, they take more responsibility for creating their own objects and factors and the relationships among them.

Methods

The process we have engaged to design curriculum materials that support student learning through inquiry has resulted in several empirically based projects that have been used by over 30 teachers and several thousand middle school students. Our program of research has shown that these projects have enabled students to learn science included in national and local curriculum standards (Krajcik et al., 2000). For each project we create achievement measures that assess student progress.

The main instrument for measuring student achievement was the use of a pre/postest. A test construction framework was developed to insure a consistent measure for each curriculum project. Each test consisted of 20 items, 18 multiple choice and 2 open response. Tests included the same proportion of content and process items (14 content and 6 process) and identical proportions of items identified as low, medium or high in difficulty (8, 10, and 2 respectively). Detemination of test item difficulty was based upon question classification system developed by Shepardson and Pizzini, (1991) and performance expectations utilized by TIMMS. Test items rated as low in difficulty required students to recall information. Medium test items required students to apply knowledge, utilize multiple representations, or understand simple relationships. Test items rated high required students to analyze data, apply investigative skills, or use concepts to explain phenomena. When possible the tests contained items from nationally recognized standardized tests such as TIMMS and NAEP.

While beyond the scope of this paper additional data was collected utilizing extensive classroom observations of teachers and students, motivation surveys, student artifacts, and in-depth interviews with students. The LeTUS curriculum projects have impacted over 4,000 students yearly across the middle grades.

Findings

Table 4 shows the number of students and teachers using LeTUS curriculum in the 1999 - 2000 school years. All students took the pre- and posttests. However, due to absences and mobility among students from the administration of the pretests and the posttests, there was considerable attrition. We are not reporting data for "Can Good Friends Mark Me Sick?" and "What is the quality of water in my river?" because data are not yet available. Table 5 presents means, standard deviations and effect size of pre and posttests. Total scores as well as scores on the content and process components are reported.

Student performance on posttests shows improvement across implementation of all projects. Table 5 shows learning outcomes by students for the current school year in the various curriculum projects for which we have analyzed data. The effect size column indicates the average gain on the posttest measured in pretest standard deviation units. Effect sizes for total score, scores on the content, and scores on process are all statistically significant.

Given the early stages of development of the units, the tests, and the teachers' capacity for enacting inquiry with technology, we believe that the data indicate that students are learning important science content related to national and local science education standards Most of this success was related to science content (the average effect size on content items was 1.1). We had less success with the process items (average effect size of .62). As we revise curricula, we will focus on improving students' opportunities to learn science processes and we will address pedagogical issues concerning science process in our teacher professional development activities. We also will need to address measurement issues regarding these important science education standards.

It is important to note that there are large effects due to teacher differences. Figure 1 compares the average gain score to the lowest and highest gain scores for the three curriculum units enacted in fall, 1999. For the Air Quality and Force and Motion units, there was considerable variability in average gains for students across the teachers enacting these units. There is less variability in the gain scores for the Big Things unit, because there were only two teachers enacting it.

Figure 2 shows the gain for each of the teachers who enacted the air quality curriculum in fall, 1999 (Figure 2 is an expansion of the data represented in the second set of bars in Figure 1). It is clear that these teachers show a substantial range of gains. The two lowest scores on this table, which in a sense are outliers, are from two teachers that have more general pedagogical problems then enacting inquiry based curriculum

Table 4

Curriculum Implementations—Number of Teachers and Students Impacted

Curriculum	Grade	When	Teachers	Students
How Can I Building Big Things? (Mechanical advantage)	6	Fall, 1999	2 (pilot)	210
Why Do I Need to Wear a Bike Helmet (force and motion)	8	Fall, 1999	8	750
What is the Quality of Air in My Community? (air quality)	7	Fall, 1999	9	900
What is the Quality of Water in My River? (water quality)	7	Spring, 2000	12	1200
Can Good Friends Make Me Sick? (communicable diseases and the immune system)	8	Spring, 2000	1 (pilot)	30

Table 5

<u>Curriculum Implementation—Student Outcomes (significance level, **p<0.01)</u>

Curriculum	Year	Number Students/Teachers	Question Type (n)	Pretest Mean (SD)	Posttest Mean (SD)	Effect Size
Why Do I Need to Wear a Bike Helmet (8th grade, force and motion)	Fall, 1999	485/8	Total (20)	6.0 (1.96)	7.18 (2.89)	.60**
			Content (14)	4.81(1.60)	5.10 (2.28)	0.58 **
			Process (6)	1.81 (1.12)	2.08 (1.17)	0.23
What is the Quality of Air in My Community? (7th grade, chemistry principles)	Fall, 1999	500/9	Total (20)	6.49 (3.04)	10.2 (4.72)	1.23**
			Content (14)	3.67 (1.86)	6.19 (3.07)	1.35**
			Process (6)	2.81 (1.93)	4.04 (2.25)	0.64**
How can I build big Things (6th grade, mechanical advantage)	Fall, 1999	179/2	Total (20)	9.78 (3.67)	14.8 (5.19)	1.36**
			Content (14)	7.03 (2.56)	10.51(3.31)	1.36**
			Process (6)	2.74 (1.55)	4.26 (2.23)	0.98**

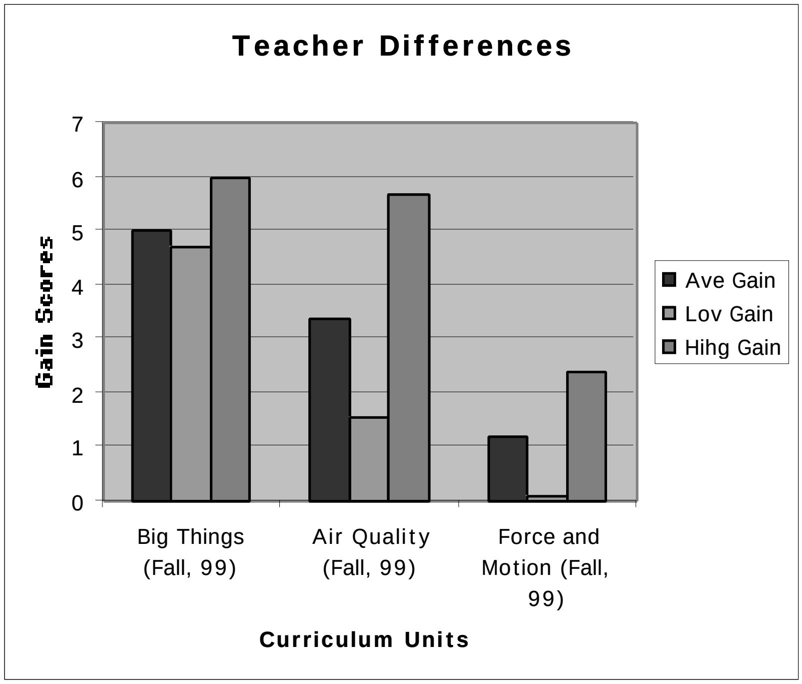

Figure 1: Teacher Difference

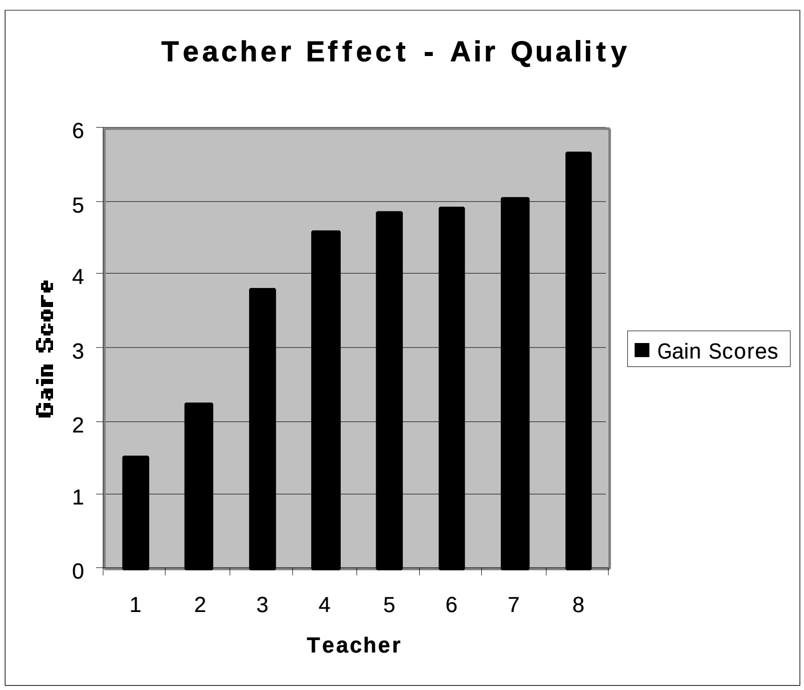

Figure 2: Teacher Effect2 – Air Quality Fall, 1999

Discussion

The data reported here show that these urban middle school students learned from an inquiry-based science curriculum supported by technology. Achievement gains were found in all curricula during the current academic year. The results, however, are not proof of success in the traditional sense. Each year there have been changes in the curriculum, the tests, addition of new teachers not experienced with the curriculum, and high turnover in student populations. Therefore, the data were not collected under controlled conditions to demonstrate consistent improvement over time or to compare effectiveness of our approach with those of others. Instead, the results should be seen as a sign that students can benefit from this approach even when it is still evolving in the setting.

In fact the results show that there is considerable variability by teacher. Like most research that includes more than one teacher, these findings show that teachers are among the many factors that can influence students' learning. We have shown elsewhere (Blumenfeld et. al, 1994) that it takes about three years for teachers to change their teaching from a more transmission to a more transformation approach. Yet, even the simple measure of the number of years a teacher has been engaged in reform efforts is not the full answer. Some teachers who were in their second year of enacting these units had students who performed at levels lower than new teachers. Obviously a range of issues interact to produce these effects. The schools serve communities that differ in many ways, including the relative economic security of the families and other indicators of social capital. There are differences in the resources available to classroom teachers in all of these schools, and administrative support varies as well. In addition to these and other factors associated with the schools, we have found that it takes several iterations of curriculum development in order to fine tune the units so that they can better engage students in science inquiry and capitalize on the possibilities afforded by new learning technologies (Singer et al., in press). Moreover, we believe that our teacher professional development activities successfully engage teachers in a range of critical learning opportunities. Yet we are convinced that we can do a better job and are in the process of revising and improving our efforts in this arena (Fishman et al., 2000).

Conclusions

Our goal is the design of curriculum materials that can promote the learning of intellectually challenging science content by diverse student populations. An additional challenge is to explore the benefits learning technologies have to promote learning. We assume that the power of new learning technologies is limited unless they become embedded in curriculum.

In this article, we described a set of design principles that, when used to create standards-based curriculum materials, could engage students in inquiry, make use of new learning technologies, and promote student learning. These curriculum principles, derived from features of social constructivism are consistent with recommendations by AAAS and NRC. Together with teachers and administrators from Detroit Public Schools, we developed five middle school science units: a sixth grade unit on mechanical advantage; seventh grade units on air quality and water quality; and eighth grade units on force and motion, and communicable disease and the immune system.

Our design of curriculum represents one member of a family of social constructivist teaching and learning approaches. The design principles and the curriculum materials we have developed from them are only one possible interpretation of the literature. Other learning environments can also result from these theoretical concepts. For instance, Linn's Knowledge Integration Environment (Linn, 1998), Edelson's "Climate Visualizer"(Edelson et. al. 1999) and Songer's Kids as Global Scientists (Songer, 1998) are based on several of the same theoretical ideas as we have described. Although these curriculum materials bear some similarity to ours, important differences exist. For example, we stress contextualization as a critical feature while Linn has articulated more of the supports necessary for students to build evidence-based arguments. Curriculum materials developed as part of Edelson's weather visualizer provide explicit supports for the development of general inquiry skills. Songer's Kids as Global Scientists emphasizes the use of telecommunications to allow access to real time data. The work of all these curriculum projects and the work we report impact student learning. Thus, we believe that the results of design research in instruction can take many successful paths.

Results show that students learn from using our curriculum materials, but we are not satisfied. Although the design principles work together to produce curriculum materials that help students engage in inquiry and use learning technologies, for each of the design principles we can do more to further articulate their use in the classroom. For instance, we can elaborate supports to promote more discourse among students. We can also develop more supports to help students learning from their own inquires. We also need to further explore the role that educative components of the material play in promoting teacher learning. Moreover, although we have carefully articulated a set of design principles and have built curriculum materials that embody these principles, we still need to create a model describing how the principles work together to promote learning. Finally, we also face challenges to support teachers in adapting our materials to best fit their local conditions.

Curriculum materials, however, present only one necessary element to promote reform. Professional development constitutes a critical component in scaling challenging materials like those described in this article throughout large urban school districts. Without policy support from administration these efforts will also fail. Systemic reform needs to address several issues simultaneously: curriculum and pedagogy, management and policy, teacher professional development, and community engagement. Such work presents challenges to school districts and educators. Reform efforts will succeed when districts and educators partner to solve these challenging issues. We have been fortunate to build such a partnership between the Detroit Public Schools and the Center for Learning Technologies in Urban Schools.

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