

Constructing Extended Inquiry Projects: Curriculum Materials for Science Education Reform

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We describe 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 design principles are derived from 4 salient features fundamental to social constructivism: active construction, situated cognition, community, and discourse. Expanding on this foundation, examples are provided for how the design principles are evinced in an actual project. We conclude with a description of challenges associated with the enactment of our curriculum materials.

Science education standards advanced by the American Association for the Advancement of Science (AAAS; 1993) and the National Research Council (NRC; 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 students need to find solutions to real problems by asking and refining questions (Bereiter & Scardamalia, 1989), designing and conducting investigations (Schauble, Glaser, Duschl, Schulze, & John, 1995), gathering and analyzing information and data (Hancock, Kaput, & Goldsmith, 1992; Vellom & Anderson, 1999), making interpretations, drawing conclusions (Chinn & Brewer, 1993), and reporting findings.

The spirit of the science education standards represents a dramatic shift in what and how science is taught in kindergarten through Grade 12 classrooms. 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, Freeman, Krajcik, & Blumenfeld, 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 (see Blumenfeld, Fishman, Krajcik, Marx, & Soloway, 2000).

In this article, we report our work on one of these issues—curriculum materials to support reform. Researchers at the University of Michigan (UM) have been working together with the Detroit Public Schools (DPS) 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 in urban classrooms. We document situations that influence technology acquisition, exploring how technology can be embedded in science

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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, Blumenfeld, Marx, & Soloway, 1994; Singer, Krajcik, & Marx, 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, Marx, Patrick, & Krajcik, 1997; Cobb, 1994; Driver, Asoko, Leach, Morimer, & Scott, 1994). 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: (a) active construction, (b) situated cognition, (c) community, and (d) 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). Perkins (1993) argued 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) as they create new understanding that builds on their prior knowledge. 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) argued that abstract and generalized knowledge gains its power through the expert's ability to apply it in specific situations. Hence, 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 (Brown, Metz, & Campione, 1996; Rogoff, 1995). Communities of practice in disciplines share cultures and, like all cultures, members have developed tools for conducting activities and regulating the community's interactions. 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. Although 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 to 10 weeks. These projects 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, Blumenfeld, Krajcik, & Soloway, 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 ad-

TABLE 1
Curriculum Design Principles

<i>Design Principle</i>	<i>Description</i>	<i>Instructional Component</i>
Context	Meaningful, defined problem space that provides intellectual challenge for the learner.	<ul style="list-style-type: none"> • Driving questions • Subquestions • Anchoring event
Standards based	Publication by larger community experts that defines the language and methods of the larger community	<ul style="list-style-type: none"> • AAAS-benchmarks • NRC-National Standards • Benchmark lessons
Inquiry	The accepted method of the scientific community for solving problems; a set of interrelated processes by which scientists and students pose questions about the natural world and investigate phenomena (NRC, 1996, p. 214)	<ul style="list-style-type: none"> • Asking questions • Data collection, organization, and analysis • Sharing and communicating data
Collaboration	Interaction among students, teachers, and community members to share information and negotiate meaning	<ul style="list-style-type: none"> • Small-group design meetings • Think, pair, share learning strategy • Group presentations
Learning tools	Tools that support students in intellectually challenging tasks	<ul style="list-style-type: none"> • Data collection • Communication • Modeling
Artifacts	Representations of ideas or concepts that can be shared, critiqued, and revised to enhance learning.	<ul style="list-style-type: none"> • Concept maps • Scientific models • Lab reports
Scaffolds	A series of methods that fade 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, 1996).	<ul style="list-style-type: none"> • Learner-centered design • Teaching strategies • Predict, observe, explain • DQB

Note. AAAS = American Association for the Advancement of Science; NRC = National Research Council. DQB = Driving Question Board.

dress the needs of diverse students (Krajcik et al., 1998; Krajcik et al., 2000; Singer et al., 1998).

Context

The contexts for curriculum projects are created through the use of driving questions. Driving questions serve to organize and guide instructional tasks (Krajcik et al., 1998; Krajcik, Czerniak, & Berger, 1999), 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 on 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 for them to be authentic and encom-

pass worthwhile science content. Due to this open-endedness, however, students have difficulty recognizing what science principles are relevant and necessary 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. 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 fundamentally different problem-solving strategies (Dunbar, 1995), and have different ways of representing information (Chi, Feltovich, & Glaser, 1981). Assisting in the developmental transformation from novice to expertise is a fundamental component of how we come to learn (Bransford, Brown, & Cocking, 1999). By using subquestions and ensuring 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 may 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 (DQB) 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 allows students to gain ownership of the project, fostering sustained student engagement.

Standards Based

The second curriculum design principle is associated with all four social constructivist features. National standards (AAAS, 1993; NRC, 1996; Rutherford & Ahlgren, 1990) 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) suggested 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. (p. 29)

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 planning, 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.

Collaboration and Student Discourse

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) called 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 may 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 ques-

tions 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 (Edelson, Gordin, & Pea, 1999; Scardamalia & Bereiter, 1996). 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, Stratford, 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 (Quintana, Eng, Carra, Wu, & Soloway, 1999; Soloway, Krajcik, Blumenfeld, & Marx, 1996). 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 commonalities 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 et al., 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. Due to the fact that 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 (e.g., planning, building, and evaluating). Projects are also designed to support students by sequencing inquiry processes 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 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 relations 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 a middle-school, project-based science curriculum.

AN EXAMPLE PROJECT: "WHAT AFFECTS THE QUALITY OF AIR IN MY COMMUNITY?"

During the 4 academic school years from 1996 through 2000, the collaborative curriculum design effort of DPS and LeTUS 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 and chemical 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 previously described.

Presented next is an example project illustrating how the design principles are manifested in a curriculum project, "What affects the quality of air in my community?" Table 3 provides an overview of this example project. The "Time" and "Subquestions 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.

Context

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 subquestions (see Table 3) developed to ensure 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 subquestion of this project is "What are the visible signs of air quality?" This subquestion 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 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 DQB.

TABLE 2
Summary of the Use of Design Principles in Curriculum Materials

<i>Design Principle</i>	<i>Social Constructivist Tenet</i>	<i>Rationale</i>
Context	Situated	Driving question and subquestion supports student engagement.
	Community	Scientific culture determines the manner that questions are framed and the manner in which they are investigated
	Active construction	Subquestions and anchoring events focus students on relations 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
Inquiry	Discourse	Provides framework for the specialized language of the community.
	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
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 are dictated by the context established by the driving question or related subquestion
	Community	Artifacts mirror representations of products constructed by community experts.
	Active construction	When artifacts are constructed and critiqued they foster discourse within the classroom.
Scaffolds	Discourse	Public sharing, critiquing, and revision of artifacts foster the active construction of student understanding
	Situated	Use of subquestions allows key concepts and processes to be made explicit.
	Community	Learners assisted by more competent members—ZPD
	Active construction	Learner-centered design of technology, provides multiple representations, hides complexities and sequences processes

Note ZPD = zone of proximal development.

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, subquestions, and concepts needed to address the relevant ideas. In addition to subquestions and the DQB, teachers employ benchmark lessons that support students' understanding of specific concepts, skills, or processes. During the exploration of the subquestions, "So, what is air, anyway?" and "How are the pollutants formed?" the teacher uses strategies in benchmark lessons (e.g., predict, observe, explain and know, want to know, and learned), whole-class and small-group discussions, and teacher demonstrations. For the first subquestion, students use a body kin-

esthetic (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 subquestion "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 may affect exhaust (e.g., number of miles on the odometer, size of engine, percent octane used as fuel, time since last oil

TABLE 3
Overview of the Curriculum Project "What Affects the Quality of Air in My Community?"

<i>Time</i>	<i>Subquestions and Associated Content</i>	<i>Instructional Component</i>
Week 1	What are the visible signs of air quality? • Sources and effects of air pollution • Introduction of driving question	• Subquestion • Anchoring event • Asking questions
Weeks 2 to 3	So, what is air, anyway? • Atoms, molecules, compounds • States of matter	• DQB • Small-group and whole-class sharing • Benchmark lessons • Modeling of compounds (e-chem) • Pre- and postrepresentations of composition and arrangement of particles in air
Weeks 4 to 6	How are the pollutants formed? • Phase changes • Indicators of chemical changes • Chemical reactions • Conservation of matter	• DQB • 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 to 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

Note. DQB = Driving Question Board.

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 examine how the pollutant levels have changed during a 5-year period and determine patterns for the pollutant levels.

Learning Tools

The students' analysis and interpretation is supported by three related learning technologies: (a) Tool Soup (Quintana et al., 1999), (b) Model-It (Jackson et al., 1996), and (c) 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, 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 con-

struction of graphs. Differences in pollutant emissions are identified and newly acquired scientific concepts concerning changes in matter are applied to explain them.

Model-It helps students make qualitative models of cause and effect relations. When using Model-It, learners create objects ("things" in the system being modeled) with which they associate measurable, variable quantities called variables. Students then define relations among variables to show how they affect each other. Relations can model immediate effects or effects over time. The application provides facilities for testing a model and a "Variable Map" for visualizing it as a whole. Students define objects, variables, and relations among the qualities of variables. For example, in building a model of air quality, air and vehicles represent objects. Variables of vehicles could include the amount of exhaust released and the number of cars in the community. Variables of air could include amount of carbon monoxide and a general quality rating. A relation 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 relations 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 three-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 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 reconstruct the same air molecules using e-chem and discuss the difference between the representations.

Artifacts

At the beginning of the exploration into the subquestion “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 previously), students reflect on and reconstruct their pictures.

These pre- and postair pictures serve as artifacts that assess the students’ changing understanding of the particulate nature of matter and as metacognitive aids for students to reflect on 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 subquestion “How are the pollutants formed?” a class discussion is used to review questions, information, and artifacts posted on the DQB. Explicit connections made dur-

ing 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 was 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 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 on 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 DQB is a support structure that assists in these cognitively demanding tasks. The DQB provides a public location in which 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, 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 videotape of presentations from previous years 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-It, which requires minimal prior knowledge from other domains.

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 transition tasks that conclude with introducing students to the new learning technology. In the transition tasks, students draw pictures of six to seven 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-It 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 variables and the relations among them.

CHALLENGES

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. Moreover, we have conducted extensive classroom observations of teachers and students using these materials and we have conducted in-depth interviews with students to determine the depth of their understanding. We have established that statistically reliable gains occur on all projects, with effect sizes ranging from about .59 to 1.36. We have also shown that it takes considerable time and effort for teachers to

learn how to teach inquiry supported with technology (Fishman, Best, Foster, & Marx, 2000) and that we have many remaining issues to address before we will be confident that student learning has been optimized. This section illustrates the challenges we must address and how they relate to the design principles.

Discourse

We argued earlier that engaging students in discourse is an essential component of constructivist approaches to teaching and learning. Several of the design principles address attempts to engage students in discourse by activities such as making their reasoning about science public through sharing predictions, observations and explanations, discussing data, and debating interpretations. Difficulties achieving intellectually engaging discourse concern teaching practices and the norms of classroom participation. Students have experienced classrooms where the norms have been to receive information or do individual seat work. The switch to a classroom that requires students to participate in intellectually engaging discourse is often foreign to students.

Some of these challenges are evident in the project entitled "What Affects the Quality of Air in My Community?" In the early stages of the project, students are asked to discuss what they know and need to know concerning air quality. This strategy is useful as a way of helping students become metacognitive about their learning; it helps them focus on what they will be doing next and it sets the stage for focusing attention on important science content. The discussion is based on the contextualizing experiences of a walk around their school, reading newspaper articles about air quality in their community, and acting a dramatization called *The Awful Eight*. These activities provide opportunities for the class to begin forming a community as students build a collective body of knowledge. With scaffolding from the teacher, the class constructs a "know and need-to-know" chart as part of the DQB. As the curriculum unfolds, the items on the chart serve as cognitive anchors for introducing and discussing why specific concepts are relevant. For example, items such as "What is sulfur dioxide?" or "How is clean air different from polluted air?" could be listed under the need-to-know chart after the performance of *The Awful Eight* play. These questions then provide a mechanism for introducing the concepts of the particulate nature of matter and chemical changes. By continually revisiting this chart and discussing if an item can be switched from the need-to-know to the know column, the classroom acts as a community and progresses in the construction of an informed response to the driving question.

Teachers need to provide students with several opportunities to use the know and need-to-know strategy successfully. The strategy requires opportunities for students to develop and share questions that are appropriate for the project's driving question. Second, students need time to critique, analyze,

and negotiate meaning of the questions that the class raises. Due to the fact that this critique is based on the existing knowledge of the classroom community, it will likely contain misunderstandings, requiring the teacher to chart a careful path to maintain student engagement while avoiding reinforcing misconceptions. Finally, the class needs opportunities to revisit the know and need-to-know lists to determine what ideas are now understood and what new questions have arisen based on newly constructed understanding.

Based on classroom observations and interviews of teachers (Taines, Patrick, & Middleton, 2000), the enactment of the know and need-to-know chart is not reaching the intended goal of facilitating a discourse community. Students are able to pose appropriate questions and teachers often post the questions on the DQB. However, the second and third steps of the strategy are rarely used. Students share their questions, but teachers have difficulty fostering discussion as an avenue for negotiating meaning or as a mechanism to navigate the curriculum. Often, when students share their questions, they address the teacher and not the class. Teachers may respond to students; however, only rarely are the questions related to other student queries or linked to the driving question. In essence, the activity becomes a series of discreet, isolated, and controlled conversations between a student and the teacher. The teacher controls both the flow and direction of information. Queries originate from the teacher (e.g., “LaShonda, can you share your question with us?”) and the response is directed back to the teacher. Each discourse event involves the teachers either as the sender or the prime recipient of the information. As a result, a discourse community is not established.

We are developing a number of strategies to support both teachers and students in fostering meaningful discourse. Curriculum materials are designed to be educative for teachers (Ball & Cohen, 1996). These educative components include example questions and probes to help teachers understand ways to foster connections between student questions and the driving question. We also are including strategies to promote more inclusive community discussion. For example, we suggest removing the teacher as the central focus of the discussion by having students call on each other as a mechanism for advancing the discussion. Additional strategies include more explicit student expectations, such as posted criteria that help students judge how their questions may relate to the driving question.

Active Construction

Active construction of knowledge is tightly linked to aspects of discourse. As students engage in exploring phenomena, and sharing and critiquing their observations and ideas, their understanding develops (Perkins, 1993; Roth, 1994). The curriculum projects use benchmark lessons to foster the understanding and connections between key scientific concepts. During benchmark lessons, teachers also introduce domain specific terminology and processes. Benchmark lessons are designed to consist of three major phases: (a) providing a pur-

pose or rationale that is related to the driving question, (b) engaging in the learning activity, and (c) making meaning of the experience. The first phase situates the activity within the larger project, the second involves the learners with the scientific concept or process, and the third provides opportunities for students to negotiate understanding. It is during this last stage that specialized vocabulary is introduced and connections are made back to the driving question. When teachers use all three phases, student conceptual understanding is fostered.

Evidence collected from classroom observations (Taines et al., 2000) indicate that many of the benchmark lessons are not fully enacted. Teachers tend to focus on Phase 2 of benchmark lessons (conducting the activity), but have difficulty with the other phases. For example, during the air quality project students engage in lessons and activities that focus on the law of conservation of matter. Students mix reagents to illustrate chemical changes (e.g., lead nitrate and potassium iodide to form the yellow precipitate lead iodide). These lessons are followed by using models (gum drops or human representations) to illustrate the rearrangement and conservation of atoms during a chemical change. During these lessons, classes followed procedures—mixing chemicals, recording observations, and building models. Students were able to complete tasks (e.g., worksheets, recall facts to the teacher) related to these assignments. Opportunities did exist for making explicit connections. These opportunities included references to *The Awful Eight* play that includes many examples of chemical changes (e.g., production of sulfur dioxide from the burning of fossil fuels) or to a prior experience involving the formation of car exhaust (e.g., class activity in which the teacher pointed out how gasoline—liquid—“enters a car” and exhaust—gas—is released by a car). However, no discussion proceeded the activity to situate the events within the larger context of the driving question. As a result of omitting Phase 1, students neither fully understand the point of the activity, nor how it connects to the driving question.

Consistent examples of Phase 3 of benchmark lessons were not visible during classroom observations. Discussions to facilitate the construction of key ideas and use of specialized vocabulary neither materialized during benchmark lessons, nor did teachers use questioning and probing strategies to facilitate student explanations of phenomena. Questions tended to be close ended without challenging students to provide rationales or evidence for their statements. Moreover, discussions were teacher centered so the class was not sharing among themselves as a community, but rather in a directed manner toward the teacher.

Teachers may not relate back to the driving question (Phase 1) or engage students in substantial discourse about the content (Phase 3) because they lack content and pedagogical content knowledge concerning fundamental science concepts. We have designed greater support for conceptual understanding through several mechanisms. These adaptations are designed to aid both students and teachers. Based on

our experience from the 1998 through 1999 enactments, projects were reconstructed to increase explicit connections to the driving question. One method to accomplish this goal was the coordinated use of anchoring events as a means to introduce benchmark lessons. Anchoring events present clearer connections between the benchmark lesson and the driving question by explicitly linking the benchmark lesson to the original contextualizing activity. For example, just prior to the benchmark lessons associated with chemical and physical changes, the students explore car exhaust. During Phase 1 of the chemical change benchmark lessons, the teacher can support the connection to the driving questions through the use of two short explicit links (i.e., benchmark lesson to car exhaust, car exhaust to driving question). A series of probing questions such as “How is what goes in a car (gasoline) different than what comes out (exhaust)?” or “What pollutants are found in car exhaust?” create these connections and provide reasons for students to think about the desired content. Beginning the benchmark lessons with a series of probing questions that focus the students on these concrete experiences (e.g., How is gasoline different from exhaust? How do you think gasoline changed into exhaust?) facilitates Phase 1.

To meet challenges teachers face in enacting constructivist teaching practice and present demanding content to children, we added teacher supports to the materials. Based on work by Ball and Cohen (1996), we address both student and teacher learning through the creation of educative curriculum materials. In creating and revising our materials, we include design features that will help teachers learn science content and inquiry. For example, we provide sample questions teachers can use to probe student understanding along with explanations about how student thinking may be engaged through these questions. We also present a range of teaching strategies that can be used to foster inquiry and we include rationales from research in educational psychology that support specific strategies. We also include materials that enrich teachers’ understanding of the subject matter.

Our research indicates that educative curriculum can facilitate teacher learning that is necessary for improved practice in reform-based science (Schneider, Krajcik, & Marx, 2000). Although educative curriculum materials cannot replace other professional development opportunities, they do have a unique role in providing professional development. Teachers can have access to materials when they need them most—during the enactment of the curriculum. In a large urban reform effort, this can be an important consideration.

CONCLUSION

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 may 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 DPS, we developed five middle-school science units: (a) a sixth-grade unit on mechanical advantage, (b) a seventh-grade unit on air quality, (c) a seventh-grade unit on water quality, (d) an eighth-grade unit on force and motion, and (e) an eighth-grade unit on 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 that we have described. Although these curriculum materials bear some similarity to ours, important differences exist. For example, we stress contextualization as a critical feature, whereas Linn articulated more of the supports necessary for students to build evidence-based arguments. Curriculum materials that were developed as part of Edelson and colleagues’ climate 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, 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 learn from their own inquiries. 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 DPS and the Center for LeTUS. Blumenfeld et al. (2000) describes our work in simultaneously addressing the complexities of reform.

ACKNOWLEDGMENTS

We thank Tony Petrosino for his comments on drafts of this article. We also thank Karen Amati, Deborah Peek Brown, Barbara Hug, Ann Rivet, and Rebecca Schneider and the entire Center for Highly Interactive Computing in Education team and the Detroit Public Schools teachers and administrators with whom we work for their continuing commitment and dedication, which is reflected in the work reported in this article. The research reported was funded with support from the National Science Foundation under the following programs: Research on Educational Policy and Practice (REC-9720383, REC-9725927) and Urban System Initiative (ESR-9453665). All opinions are the responsibility of the authors and no endorsement by the National Science Foundation should be inferred.

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