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Design-Based Science and Student Learning

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Abstract: Design-Based Science (DBS) is a pedagogy in which the goal of designing an artifact contextualizes all curricular activities. Design is viewed as a vehicle through which scientific knowledge and real-world problem-solving skills can be constructed. Following Anderson and Hogan's (1999) call to document the design of new science pedagogies, this goal of this article is twofold: (a) to describe DBS, and (b) to evaluate whether significant science knowledge was constructed during consecutive enactments of three DBS units. In this study, 92 students participated in the consecutive enactments of three different DBS units. The development of their scientific knowledge was assessed through posters and models constructed during the curricular enactments and by identical pre- and post-instruction written tests. The posttests showed considerable gains compared with the pretests, while the models and posters show application of this newly constructed knowledge in solving a design problem. These positive results support efforts being made to restructure school science around inquiry-based curricula in general and design-based curricula in particular. © 2004 Wiley Periodicals, Inc. J Res Sci Teach 41: 1081–1110, 2004

Most real-world problems are ill-defined, lacking required information, and not having a known correct nor best solution (Frederiksen, 1986; Glass, Holyoak, & Santa, 1979; Nickerson, 1994; Reitman, 1964; Roberts, 1995). School science has traditionally been built around well-defined problems, such as predicting an ideal projectile's trajectory. Much of the curricula and

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teaching practices used in schools have been criticized because their academicism does not give students experience grappling with real-world problems in situations where decisions are not clear cut. Several researchers and organizations have recommended restructuring school science around real-world issues, using pedagogical frameworks that will help students develop the knowledge and skills necessary in a science and technology rich world (AAAS, 1990; Bartel, Lichtenberg, & Vaughan, 1992; Blumenfeld, Soloway, Marx, & Krajcik, 1991; Lipman, 1991).

Following these recommendations, a number of K-12 science programs have been developed that stress inquiry (CTGV, 1992; Krajcik, Blumenfeld, Marx, Bass, Fredricks, & Soloway, 1998; Linn, 1997; Penner, Lehrer, & Schauble, 1998; Songer, 1996). Evidence gathered from these and other inquiry-based programs has taught us much about students' abilities and difficulties when they are required to struggle with ill-defined problems. For instance, we have learned that children tend to generate low-level factual questions rather than questions that could extend their understanding (Scardamalia & Bereiter, 1992), that students do not consider evidence systematically in formulating arguments (Linn, 1992), and that students are proficient at carrying out procedures but have difficulty focusing their attention on the reasons for these procedures (Krajcik et al., 1998).

Several inquiry-based programs have been developed at the University of Michigan, of which one is Design-Based Science (DBS). DBS aims to help students construct scientific understanding and real-world problem-solving skills by engaging them in the design of artifacts. The creation of the artifacts in DBS is not viewed as a culminating experience, where the students attempt to apply scientific knowledge that was constructed in the traditional manner of focusing on well-defined problems to a real-world problem; instead, the design experiences lie at the heart of the DBS curricula. All scientific knowledge and problem-solving skills are constructed in the context of designing artifacts as particular instances of solving ill-defined, real-world problems.

In order to justify the faith the education community has in these and other inquiry-based programs, it is necessary to establish that they lead to significant learning. The purpose of this article is to describe the DBS pedagogy and to evaluate whether the enactment of DBS curricula lead to the construction of substantial scientific knowledge.

Why Use Design as a Vehicle for Learning Science?

Design is "the area of human experience, skill and understanding that reflects man's ... appreciation and adaptation of his surroundings in the light of his material and spiritual needs" (Royal College of Art, 1976, p. 3). We all naturally engage in design. Since we all use tools and materials purposefully in trying to adapt the environment to one that suits our needs, the capacity for design must be a fundamental human aptitude (Roberts, 1995). Indeed, children's "play" incorporates many of the characteristics of "designerly" activity (Baynes, 1994). Design-based activities have the potential, therefore, to address a basic capacity existent in all students.

However, we should distinguish between design as an everyday activity and Design (capital D) as an activity in which professional designers engage. The distinction between the two lies in their differing degrees of formalization: while everyday design is often spontaneous and intuitive, with the designer unaware that she is engaged in a problem-solving process that could perhaps be improved upon, Design is a formal process, and may include many explicit stages and criteria for determining whether the outcomes of the design process are acceptable. Everyday designers often err in their decisions and considerations; the formal Design process attempts to minimize the chances that Designers will do so as well.

Simon (1999) felt that there was no fundamental difference between Design and many other real-world activities, which are by and large also "ill-defined": "The intellectual activity that produces material artifacts is no different fundamentally from the one that prescribes remedies for a sick patient or the one that devises a new sales plan for a company or a social welfare policy for a state'' (Simon, 1999, p. 111). Design is a particular, but representative, instance of real-world problem-solving, having no prescribed path leading from the requirement specification to the final design product (Bucciarelli, 1994). Often there is no clear definition of when an acceptable solution has been reached. Seldom can one determine if a design product is the best response to the requirements. Any Design product is the result of a wide range of value judgments. Design seems to be especially akin with science, which is also an ''ill-defined'' problem-solving activity: ''There simply is no fixed set of steps that scientists always follow, no one path that leads them unerringly to scientific knowledge'' (AAAS, 1990, p. 4).

Not surprisingly, the activities that comprise the Design process (Davis, Hawley, McMullan, & Spilka, 1997), the design skills recommended that students develop (ITEA, 2002), and the inquiry activities that were recommended in the National Science Education Standards (NRC, 1996) coincide with one another (Table 1).

Is it reasonable to create a science pedagogy structured around the design process? A design-based science pedagogy could build on students' natural and intuitive experience with design. As the activity of design develops the cognitive modeling and representative capacity of the mind (Roberts, 1995), a design-based science pedagogy could also help students develop the modeling and the representational abilities that are needed in scientific domains (Nickerson, 1994). Several researchers and organizations have suggested incorporating design activities into education in general and in science education in particular (AAAS, 1990; Chiapetta, Koballa, Jr., & Collette, 2002; Davis, 1998; ITEA, 2002; Layton, 1993; NRC, 2002).

The idea of combining science and design in classrooms has received much attention in the United Kingdom (Layton, 1993). However, rather than using design as a vehicle to support the learning of science, the British have chosen to teach science first and then apply this knowledge to the solution of design problems.

A few American science education programs have been developed that make use of design activities (Kafai & Ching, 1998; Kolodner, Crismond, Gray, Holbrook, & Puntambekar, 1998; Penner et al., 1998; W.-M. Roth, 1996; TERC, 2000). A middle school program called *Learning By Design*$^{\text{TM}}$ *(LBD*$^{\text{TM}}$*)* has been developed at the Georgia Institute of Technology (Kolodner et al.,

Table 1
Comparison of design and scientific inquiry

Design Process	ITEA Technology Standards	NSES Inquiry Standards
Identify and define the problem	Identify a design problem	
	Decide whether or not to address it	Pose questions
Gather and analyze information	Identify criteria and constraints	Review what is already known
Determine performance criteria for successful solutions	Determine how these will affect the design process	Make predictions
Generate alternative solutions and build prototypes	Refine and evaluate a design solution by using conceptual, physical and mathematical models	Plan investigations Consider alternative explanations
Evaluate and select appropriate solutions		
Implement choices	Develop and produce a product or system	Make observations Gather, analyze, and interpret data
Evaluate outcomes	Evaluate final solutions	Propose answers and explanations
	Communicate the results of the entire process	Communicate results

1998). It is based on a conceptual framework taken from Case-Based Reasoning (Kolodner, 1993) and classroom practices taken from Problem-Based Learning (Barrows, 1985). This program is similar to DBS but predates it by four years. It is built on multiple iterations of constructing, evaluating, and revising models, along with discussion of issues that arise while solving the design problem. Each iteration focuses on the same science concepts, only at increasing levels of complexity. As will be described later, we too chose to give our program an iterative structure. However, instead of having each iteration focus on similar science concepts, each iteration in our program focuses on different science concepts.

Penner et al. (1998) had children design models of the human elbow in order to motivate an exploration of the biomechanics of the human arm. This study focused on the development of models by the students and on the importance of these artifacts in the learning process. The children were given the goal of building something that functioned like an elbow, without specifying any particular details. Over five class periods, their models were built, compared, evaluated, and modified. Then, using a teacher-built model, an exploration into the effects of load and bicep location on an arm was conducted. The results of this study, which showed that the goal of designing an artifact can serve as an effective context for science learning, supported our decision to do likewise.

Using the EFCS curriculum (Engineering for Children: Structures), Roth (1996) had students spend most of their time constructing towers, bridges, and huts. He was especially interested in the importance these artifacts played in the social construction of knowledge. This study showed that in some cases the students collectively ‘‘discovered’’ the *engineering* knowledge needed to create an acceptable artifact. However, it is questionable whether the students understood the scientific principles underlying their engineering knowledge. From this study we learned that the relation between engineering concepts and their underlying scientific principles need to be explicitly exposed for them to be apparent to students.

In Kafai and Ching’s (1998) program, groups of students collaborate in designing computer software that deals with a scientific topic, such as neuroscience. The software is meant to help younger students learn topics in neuroscience. The students are responsible for selecting their research questions, implementing them in software, and managing themselves during the design process. In this case, the design projects are a culminating experience; the students have learned some neuroscience beforehand and are implementing, grounding and applying their knowledge in these projects.

In the *Science by Design* series, TERC (2000) developed four separate high school units called *Construct-A-Glove, Construct-A-Boat, Construct-A-Greenhouse* and *Construct-A-Catapult.* In the *Construct-A-Glove* unit, for example, the students receive a design brief and instructions for building and testing a glove. Then, working in teams, they gather data about different insulation materials, compare different gloves, and learn about homeothermic feedback through simple experiments. The students then design a glove, build a prototype, test its performance, and present their results to the other student teams. Unlike our program and unlike LBD, the TERC units are composed of a single cycle. We felt that for the new concepts to be understood deeply the need to be revisited several times, each time in different contexts. Thus, in DBS, while each cycle introduces new concepts, it also returns to the concepts presented in the former cycles.

Of these programs, only that developed at TERC is for high schools and only LBD^{TM} is iterative. In these two programs, design is the vehicle for constructing new science knowledge; in the others, design and science are done sequentially, first designing and then learning the underlying science concepts (Penner et al.) or first learning the science concepts and then using them to design an artifact (Kafai and Ching).

Despite the existence of these programs, the use of design activities in science classes in US schools remains an isolated practice that has its strongest support at the level of the individual teacher (Davis et al., 1997).

Design-Based Science (DBS)

We have developed three ninth-grade DBS units that serve as a context to explore whether DBS curricula support construction of scientific knowledge and ‘designerly’ problem-solving skills. All three units are cyclic and are structured around *design problems* chosen to be interesting and challenging to the students. The creation of the artifacts in DBS is not viewed as a culminating experience, where the students attempt to apply scientific knowledge that was constructed in the traditional manner of focusing on well-defined problems, to a real-world problem; instead design experiences lie at the heart of the DBS curricula. They contextualize all the curricular activities.

DBS has much in common with other inquiry-based programs, even those that do not use design activities, such as *Scientists in Action* by the Cognition and Technology Group at Vanderbilt (CTGV, 1992) and Project-Based Science by the hi-ce group at the University of Michigan (Krajcik et al., 1998). Some of the characteristics common to these programs are (Blumenfeld, Marx, Soloway, & Krajcik, 1996): (a) they are centered around authentic tasks for prolonged periods of time, (b) they lead to the creation of artifacts by the students, (c) they encourage the use of alternative assessments, (d) they make use of computer-based technology, (e) they build upon student collaboration, and (f) they view the teacher as a facilitator and a learner along with the students rather than as a source of knowledge.

In the first of the DBS units, called “*How do I Design a Structure for Extreme Environments?*” the goal is to design and build a model house that can withstand extreme environmental conditions. In the second unit, called “*How Do I Design a Battery That Is Better for the Environment?*” the goal is to design and build a wet cell that makes use of nontoxic materials. In the third unit, “*How Do I Design a Cellular Phone That Is Safer to Use?*” the goal is to design a cellular phone that minimizes potential radiation and sound hazards without compromising customer appeal. All three units incorporate the explicit goal of meeting state and US national curriculum standards (Michigan Department of Education, 1996; National Research Council, 1996). The alignment of each unit with state and national science curriculum standards is presented in Appendix A.

Each unit begins with the presentation of a *design specification* that includes the requirements the students’ models are expected to fulfill. Thus, the students know in advance what the unit is about and what is expected of them.

Our goal in these units is not to instruct the students about Design; we want them to engage in Design in order to learn science. Therefore, to enable the students to engage in design without having to teach them about it (Mamlok, Dershimer, Fortus, Krajcik, & Marx, 2001), each unit is organized around a learning cycle as shown in Figure 1. The stepwise description of the design process mentioned earlier (Davis et al., 1997) and a social constructivist perspective (Blumenfeld, Marx, Patrick, Krajcik, & Soloway, 1997) were considered while deciding on the structure of the learning cycle. Unlike LBD^{TM}, where each iteration focuses on similar science concepts. but at increasing levels of complexity, in DBS each cycle focuses on different content in the design problem. In order to acquaint the students with the stages in the design process, each cycle is usually completed in an orderly manner; there are, however, some cases that short-circuit steps in the cycle, or have steps executed out of order, as is to be expected in a nonlinear process.

The *How Do I Design a Structure for Extreme Environments?* unit is composed of 5 learning cycles, dealing with weather conditions, technical drawings, different sources of loads, shape and

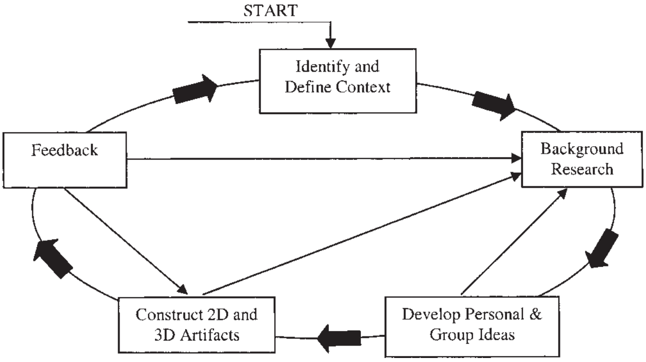


Figure 1. The Design-Based Science learning cycle.

structural integrity, and thermal insulation. The *How Do I Design a Battery That Is Better for the Environment?* unit is composed of 4 cycles, dealing with toxic materials and their disposal, different types of batteries, the materials from which they are made, and the health hazards related to these materials, how batteries decay and how to measure this, and electric circuits and electrochemistry. The *How Do I Design a Cellular Phone That Is Safer to Use?* unit is composed of five learning cycles, dealing with the potential hazards of EM radiation, the historic form and function development in telephones, general wave characteristics, sound waves, and EM waves. In each cycle, students conceive, design, construct, and modify either 2D or 3D models of structures for extreme environments, batteries that make use of safe materials, or cell phones that pose less of a potential hazard to their users.

During the unit enactments, a poster of the learning cycle is hung on the wall at the front of the classroom. The learning cycle is presented to the students near the start of the first cycle of each unit, and then it is mentioned at the start of each lesson, with the teacher pointing out how the day's planned activities fit in the cycle.

Step 1: Identify and Define Context

Each cycle begins by setting the context for the cycle's activities. Learning can be improved when abstract arguments are embodied in contexts significant to the learners (Wason & Johnson-Laird, 1972). Context supplies significance for the tasks the students will be facing and provides trigger points for action—things the students can immediately begin to investigate (Kimbell, Stables, & Green, 1996). For instance, the first cycle in the *Extreme Structures* unit begins by showing the students films depicting an arctic blizzard and a Sahara sandstorm. This leads directly to a research activity in which the students inquire into the weather conditions (temperature, precipitation, and wind speed) typical of these two different extreme environments.

Besides supplying significance and trigger points for action, contextualization affects the ability to transfer knowledge. It is important to teach a subject in several contexts, since knowledge transfer is especially difficult when learned in a single context (Bjork & Richardson-Klavhen, 1989). By teaching a subject in multiple contexts, there is a greater chance that the students will succeed in abstracting the main concepts, which leads to a more flexible knowledge representation and enhanced ability to apply the knowledge in new contexts (Gick & Holyoak, 1983). These units present each concept in at least two different contexts. For instance, thermal insulation is discussed in the context of a house, an ice cube in a tin can, and a cup of hot chocolate.

Step 2: Background Research

Background research can be in the form of benchmark lessons in which the teacher presents new scientific concepts, reading selected materials, searching and gathering relevant information, sharing on a whiteboard of data collected in group experiments and then collectively analyzing the complete database, teacher-led demonstrations, computer-based simulations of relevant phenomena, and a virtual expedition to examine appropriate primary sources.

As an example, working in groups of four in a jigsaw activity, students in the *Extreme Structures* unit investigate the dependency of a beam's vertical deflection on the mass of a weight being hung from its center and on the distance between the beam's two support points. Each group is given a yardstick (beam), which they support between two tables (pillars); every group places their tables at different distances one from the other (different spans). They then hang a series of weights from the center of the yardstick, measure the yardstick's vertical deflection for each weight, and create a graph showing the yardstick's deflection vs. hung mass. The teacher prepares a table on the whiteboard where each row represents a different span and each column represents a different mass. The cells in the table represent the various vertical deflections. A representative from each group fills out the cells in a particular row according to the group's measurement. The teacher also prepares an empty graph whose axes represent deflection and hung mass. Using different colored markers, representatives from each group draw a different deflection vs. mass curve. After discussing the results, explaining how span is a varying parameter in this graph, and clarifying any misunderstandings, the teacher shows how the same results can be depicted differently, as span vs. hung mass with deflection as the varying parameter. Thus, for a known mass, students can select the span that will give a desired deflection. The teacher explains that this is how an architect would approach the problem and how they can use what they've learned in the investigation in designing their structures, by knowing the mass a beam has to hold and knowing the maximum vertical deflection the beam (roof) can tolerate; you can determine the maximum distance between the pillars supporting the beam.

One of DBS's goals is to give students experience in grappling with real-world problems. Solving most real-world problems involve the need to construct new knowledge relevant to the problem. A factor that distinguishes the expert from the novice is the expert's understanding that novel problems often cannot be solved with existing knowledge alone, but that new knowledge may need to be learned (Wineburg & Fournier, 1994). The existence of a learning stage in the process of design, and of solving problems in general, is explicitly and repeatedly pointed out to the students; calling attention to a designer's need to learn helps impress upon our students the importance of continuous learning, even for design experts. This resonates strongly with Bransford and Schwartz's (1999) claim that one of the major objectives of education is to prepare students for further learning.

Step 3: Develop Personal and Group Ideas

According to social-constructivist theory, learning is seen as an active, continuous process; learners, using prior experience and knowledge, construct and adapt meanings and interpretations of new knowledge obtained by interacting with social and inanimate environments (Driver & Bell, 1986; K.J. Roth, 1990; Wittrock, 1974). In DBS, activities are carried out on four levels: individual, pairs, groups of four, and the entire class.

Following the background research stage, every student comes up with his or her own design solution, be it a method to prevent the roof of a structure from sagging, or a scheme for decreasing the amount of EM radiation absorbed by the head while using a cell phone. As it has been shown that group problem solving that involves open-exchange and elaborate discussion among group members can enhance student learning (Cohen, 1994; Evans, 1989; Sharan & Sharan, 1989), the students present their solutions to their group members; the group decides which of the four suggested solutions they prefer or perhaps they decide to combine the solutions in some manner, and they write a justification for their decision. By providing an opportunity for the students to contrast their own thinking with that of others, the students begin to develop a critical appreciation of the different aspects of the problem (Schwartz & Bransford, 1998) that will assist them in learning new and related information.

Because people construct new knowledge more effectively by contemplating their physical and mental actions while interacting with more knowledgeable others (Vygotsky, 1986), and in order to make sure that they are not heading off-track, the teacher critiques each group during this process of selecting and justifying a decision.

Step 4: Construct 2D and 3D Artifacts

In the next stage, each design team splits into pairs, with each pair constructing a model or modifying an existing model based upon the design solution their design team decided on in the former stage. The model may be a three-dimensional (3D) model of a house or a cell phone antenna shield, or it may be a cut-away drawing of an electrochemical cell. The construction work is done in pairs, rather than in teams, in order to provide each student with as much hands-on interaction as possible with the various aspects of their models. This is the stage when the students' ideas are concretized. Concepts and notions that may have been vague and unspecific need to be reevaluated and reorganized in order to allow them to guide the development of a material artifact. The students realize the appropriateness and reasonableness of some of their ideas, and the unsuitability and impracticality of others, opening the way for some conceptual models to become entrenched and others to be replaced (Strike & Posner, 1992).

After each pair has constructed or modified a model, they rejoin their design team members to discuss and compare their models. They decide which model is superior and then prepare a document to justify it; this justification is based on the document they wrote in their design teams in the former stage and the experience they gained while constructing, modifying, and comparing their model.

Since every team is divided into two pairs, and each pair builds a model according to a solution agreed upon by the entire design team, the two models built by the two pairs should bear great resemblance to each other. However, since the students' ideas and understandings are themselves modified while constructing the physical models, there is also some variance between the two models. Close inspection and analysis of these models can provide both the students, the teacher, and the researchers a window to the students' understandings (Brown & Shavelson, 1996). This inspection is carried out in the next step in the step.

Step 5: Feedback

Ongoing formative assessment provides students with opportunities to revise and improve their understanding, thus supporting their learning (Vye, Schwartz, Bransford, Barron, Zech, & CTGV, 1998) Therefore, students' models are subjected to physical tests whenever possible, and they are presented several times to the entire class in a pin-up session (Kolodner et al., 1998; Schön, 1985) in which the models are laid out or hung up and the entire class moves from model to model, listening to the student-designers' descriptions and the teacher's comments, and offering their own critique.

Not every model built is assessed. Every design team builds two models and decides which one they think is superior. In order to maintain a reasonable limit to the time spent on the feedback sessions, only these ‘‘select’’ models are critiqued or tested.

When subjecting their models to physical tests, such as determining whether a model house provides sufficient thermal insulation or an electrochemical cell sufficient voltage, the students are not only testing their models to see whether they meet their specification’s requirements, they are also learning about testing procedures in general. They learn how the physical characteristic being evaluated determines what type of data needs to be measured, what other characteristics need to be controlled, how to organize, and how to analyze the data.

Likewise, while receiving and giving feedback in a pin-up session, they are not only learning about the pluses and minuses of their own model; they are learning how to present their ideas clearly and simply so that others may understand and how to focus on the main ideas. They are also learning from the comments given to their peers’ models, who may have thought of something that they didn’t.

Methods

The call for scientific literacy for all means that students should be able to use what they learned in schools in their extra-school lives. Clearly, one cannot transfer knowledge to new contexts unless it was constructed in the first place. The purpose of this study was to assess whether consecutive *enactments* of DBS units led to the construction of substantial scientific knowledge. Our use of the term *enactment* includes all the variables that come to play when a teacher and students meet in order to teach and to learn. Three types of data were collected:

Pre-instructional written tests
Post-instructional written tests
Models created by the students during the curricular enactments

Setting and Participants

This study was conducted in three ninth- and tenth-grade physical science classes taught by one teacher at the single public high school of a small industrial town located near a large Midwest urban area during the 2001–2002 school year. There were 600 students at this school, almost all from blue-collar families. Nineteen percent of them were entitled to free or reduced price lunch.

The teacher had 3 years’ experience teaching full-time, having taught night and summer classes in the past. He had a bachelors degree in earth science education with a minor in geography. He was certified to teach earth, physical and integrated science, geography, history, government, and economics, all at the secondary level.

Although this was the first time the teacher taught either the *Environmentally Safe Batteries* unit or the *Safer Cellular Phones* unit, he had taught an earlier version of the *Extreme Structures* unit during the previous school year. Other than that he had no former experience using any kind of inquiry-based curriculum. The school’s principal had originally chosen the teacher, along with another one, to enact the *Extreme Structures* unit during in the 2000–2001 school year. The teacher who participated in this study chose of his own accord to enact all three DBS units during the 2001–2002 school year. During the period in which he enacted these units he participated in several professional development sessions that focused on the unit.

The enactment of the *Extreme Structure* units lasted 8 weeks, that of the *Environmentally Safe Batteries* 3½ weeks, and that of the *Safer Cellular Phones* 6 weeks. Each week consisted of 5 classroom hours.

In all, 92 ninth- and tenth-grade students in three physical science classes participated in the study. 86% of the students were white, 11% were hispanic, 2% were black, and 1% were Asian; 56% were female. There was a 16% turnover—5 students who were present when the study began left before it ended, and 10 students joined the classes in the middle of the study. Nine students participated in two enactments of the *Extreme Structures* unit; having received failing grades during the 2000–2001 school year, they were required to retake a physical science class. As specified by the curriculum, the teacher allowed the students to form self-selected groups of four.

Procedure

The three DBS units were enacted consecutively, starting with the *Extreme Structures* unit, then the *Environmentally Safe Batteries* unit, and finally the *Safer Cellular Phones* unit. A preinstruction science content knowledge test that aligned with the content of the unit was administered on the first day of each unit's enactment. Each enactment ended with a post-instruction test, which was identical to that unit's pre-instruction test and served as a final exam. Artifacts, such as 3D models and posters, were collected or photographed during the units' enactment. One of the authors was present for about one third of all the class sessions throughout all three enactments.

Instruments

Pre- and Post-Instructional Science Knowledge Tests. The students' understanding of the science content in each unit was assessed before and after each unit was enacted by identical pre- and posttests. There were three different tests, one for each unit. The tests were developed according to a model elaborated by the hi-ce research group at the University of Michigan (Singer, Marx, Krajcik, & Chambers, 2000). The tests were composed of multiple-choice items and open-ended items that probed for different levels of comprehension using low, medium, and high cognitive demand items. The multiple-choice questions were low and medium demand items; the open-ended questions were medium and high demand items. The tests focused on the specific science content that was addressed in each unit in contexts similar to those used in each unit. Examples of items from each of the tests are presented in Appendix B, where item 1 is a low-demand item, items 2 and 3 are medium-demand items, and items 4 and 5 are high-demand items. The rubric for the *Extreme Structures* unit is presented in Appendix C. The teacher used the post-instructional tests as his final exams for the respective units.

On each test, one point was given for each correct response to a multiple-choice item. Each open-ended subitem was also worth one point, but less than that was given if the subitem was not responded to fully. Thus, if a full response to an open-ended subitem consisted of two parts, for instance, selecting an optimal roof shape for a given situation and changing a structure's foundation, each part of the response was worth ½ point, so the item could be scored either 0 points, ½ points, or 1 point.

The test for the *Extreme Structures* unit was composed of 15 multiple-choice items and 3 open-ended items comprised of 8 subitems. The maximum attainable score on this test was 23 points. The test for the *Environmentally Safe Batteries* was composed of 14 multiple-choice items and 2 open-ended items comprised of 8 subitems. The maximum attainable score on this test was 22 points. The test for the *Safer Cellular Phones* was composed of 13 multiple-choice items and 5 open-ended items comprised of 8 subitems. The maximum attainable score on this test was 21 points.

All the tests were scored by one of two raters. In order to achieve an inter-rater reliability above 95%, the following was done: Five student samples of each pre- and posttest were scored by both raters. The ratings were compared with each other and the wording of the scoring rubrics was modified in order to better represent the raters' common understanding. Five more student samples were then scored by the raters and again the ratings were compared. Based on these final samples, the inter-rater reliability for all six pre- and posttests was better than 99%.

Models Created by Students

Student learning was also assessed through artifact analysis. As was described earlier, each group of students created and modified 2D and 3D artifacts throughout the units' enactments: a 3D model structure for extreme environmental conditions, a poster of a recyclable liquid battery that they constructed and tested at home, and a poster of a cellular phone that incorporates novel safety features. Unlike the model structure and the cell phone poster, which were modified throughout their respective units, the liquid battery was constructed and tested only at the end of the *Environmentally Safe Batteries* unit, since the students had little understanding at the start of this unit of how an electrochemical cell is constructed. Also, unlike the model structures and the liquid batteries, which were subjected to physical test, the cellular phone posters were not. No functional cellular phones were built by the students; only posters of cellular phones. This does not mean that the students were not as engaged in "designerly" activities in this unit as in the others; designers often first construct paper-based or computer-based representations of their ideas before constructing a functional prototype (Bucciarelli, 1994).

Inspection of these models can provide a window into the students' understandings (Brown & Shavelson, 1996; Shavelson, Baxter, & Pine, 1991) and present additional evidence, beyond that supplied by the science content tests, that relevant science knowledge was constructed. Scoring rubrics were developed for each artifact. These rubrics were checklists that assessed which concepts were considered in creating and testing the artifacts, and whether the conclusions resulting from the use of these science concepts were correct.

All the artifacts were scored by either the teacher or the authors. In order to achieve an inter-rater reliability above 95%, the following was done: Two student artifacts from each unit were scored by both raters. The ratings were compared with each other and the differences clarified in order to obtain a common understanding between the raters. Two more student artifacts from each unit were then scored by both raters and again the ratings were compared. Based on the scoring of these artifacts, the inter-rater reliability for all the artifacts was better than 99%.

Results

Pre- and Posttests

While 92 students participated at one time or other in the study, 70 of them completed both the pretest and the posttest for the *Extreme Structures* unit, 64 completed both the pre- and posttest for the *Environmentally Safe Batteries* unit, and 56 completed both pre- and posttest for the *Safer Cellular Phones* unit. Only the scores of these students were used in the following analyses.

Independent sample t tests (two-tailed, alpha = .05) were computed for each unit in order to determine whether the students who did a unit's pretest, but not its posttest, differed from those who completed both tests, thereby biasing the posttest results. These t tests showed that it was unlikely that these groups of students differed in terms of their knowledge at the start of each unit ($t = 0.50$, $df = 70$, $p = 0.62$ for *Extreme Structures*; $t = 0.46$, $df = 67$, $p = 0.65$ for *Safe Batteries*; and $t = 0.22$, $df = 64$, $p = 0.83$ for *Safer Cellular Phones*).

Table 2
Statistical measures of pre- and posttests

	Pretest		Posttest					
	Mean	Standard Deviation	Mean	Standard Deviation	Degrees of Freedom	*t*	*p*	Effect Size
Extreme structures	7.9	3.3	14.7	2.9	69	16.9	<0.001	2.1
Environmentally safe batteries	6.8	2.7	11.9	2.9	63	15.3	<0.001	1.9
Safer cellular phones	4.0	2.7	11.2	3.7	55	14.5	<0.001	2.7

Paired t tests (one-tailed, alpha = .025) were used to determine whether the means of the posttests were statistically different than those of the pretests. To determine the degree to which the results diverged from the null hypothesis (Thompson, 2002), an effect size using the posttest mean, the pretest mean, and the pretest standard deviation (SD) were calculated for each pre-/posttest pair. The results are presented in Table 2. The paired t tests and the effect sizes revealed that it was highly unlikely that the significant difference between all three pairs of tests was mere chance.

Since the students received no feedback from the pretests, there is little reason to think that these gains might have been due to taking the same test a second time. All the same, we compared the posttest results of students who participated in the pretest with those of students who did not. These independent samples t tests (two-tailed, alpha = .05) showed that it was unlikely that the gains were due to test retake ($t = 1.98$, $df = 80$, $p = 0.04$ for *Extreme Structures*–the students who participated in the pretest scored lower on the posttest than the students who didn't participate in the pretest; $t = 0.66$, $df = 68$, $p = 0.51$ for *Safe Batteries*; and $t = 0.29$, $df = 62$, $p = 0.77$ for *Safer Cellular Phones*).

We define high achievers as those students who scored above the median in a pretest and low achievers as those who scored below the median. We split the results into two groups along the median and compared the gains of both groups. The results, which are presented in Table 3 show that learning gains occurred for both high and low achievers. Others analyses show that there may have been ceiling effects in *Extreme Structures* and *Safe Batteries* posttests.

Unlike the other pretests, the results of the *Safer Cellular Phones* pretest show that the students had practically no early understanding of the main topic dealt with in the unit, wave concepts. They seemed to be randomly guessing in the multiple-choice items and either left the open-ended items blank or responded "I don't know." The unusually large effect size for this unit was obtained due to the poor pretest scores rather than due to posttest scores that were higher than those obtained in the other two units.

Table 3
Pre/posttest gains for different achievement levels

		Mean Gain	
	Pretest Median	Low Achievers	High Achievers
Extreme structures	7.9	8.3	5.3
Environmentally safe batteries	6.7	6.4	3.7
Safer cellular phones	3.0	8.0	6.4

Analysis of Models

Extreme Structures Unit. All the early (built in the first cycle) and late (built in the last cycle) model structures, a total of 20 models, were analyzed in detail and scored using the rubric appearing in Table 4, which also presents the mean scores given to these models and the scores given to an exemplar model. This model is described in detail in following paragraphs. It was chosen for detailed description because its late version scored 14, which was less than 1 SD above the mean. Thus, it can be considered a good, but representative example.

Figure 2 is a photograph of the ‘‘early’’ exemplar model structure built at the start of the unit by a group of students. This early model was built after they had learned about scaling and technical drawings, but before they had constructed any new understanding about structural integrity, roof shapes, or thermal insulation. The model is made of construction paper and white glue. It is a parallelepiped of dimensions 5.0 in. × 4.0 in. × 3.5 in., which is supposed to be a 1:39.4

Table 4
Model structure scores

Score	Content Criteria: (23 points for all sections)	Exemplar Model		Mean (SDEV)	
		Early	Late	Early	Late
	Dimensions and General Features (10 points):				
__________	All three dimensions are scaled correctly. (3)	1	3	1.8 (0.8)	2.4 (0.9)
__________	There is one door and one window. (2)	2	2	1.4 (0.5)	1.4 (0.5)
__________	The door is large enough to pass through. (1)	0	1	0.4 (0.5)	0.4 (0.5)
__________	The door and window are on opposite sides of the structure. (1)	0	1	0.2 (0.4)	0.8 (0.4)
__________	The window can be opened and sealed. (1)	0	0	0.4 (0.5)	0.2 (0.4)
__________	The door can be opened even when there is snow or sand piled against it. (1)	0	0	0.0 (0.0)	0.4 (0.5)
__________	Oriented according to predominant wind direction. (1)	0	1	0.0 (0.0)	0.4 (0.5)
__________	Subtotal	3	8	4.2 (1.0)	6.0 (2.3)
	Construction and Transportation (2 points):				
__________	Construction materials chosen for light weight (ease of transportation). (1)	0	1	0.0 (0.0)	0.8 (0.5)
__________	Structure easily constructed. (1)	0	1	0.0 (0.0)	0.8 (0.4)
__________	Subtotal	0	2	0.0 (0.0)	1.6 (0.4)
	Foundation (2 points):				
__________	Anchored to the ground. (1)	0	0	0.0 (0.0)	0.4 (0.5)
__________	Floor (1)	1	0	0.4 (0.5)	0.6 (0.5)
__________	Subtotal	1	0	0.4 (0.5)	1.0 (1.0)
	Roof (2 points):				
__________	Slanted against snow collection (1)	0	1	0.0 (0.0)	0.4 (0.5)
__________	Supported by pillars. (1)	0	1	0.0 (0.0)	0.8 (0.4)
__________	Subtotal	0	2	0.0 (0.0)	1.2 (0.5)
	Thermal Considerations (4 points):				
__________	Walls insulated. (1)	0	1	0.0 (0.0)	0.6 (0.5)
__________	Windows double paned. (1)	0	0	0.0 (0.0)	0.0 (0.0)
__________	Windows shaded (1)	0	0	0.0 (0.0)	0.2 (0.4)
__________	Walls colored bcenter or dark (1)	0	1	0.0 (0.0)	0.8 (0.4)
__________	Subtotal	0	2	0.0 (0.0)	1.6 (0.9)
__________	Total	4	14	4.6 (1.0)	11.4 (4.2)

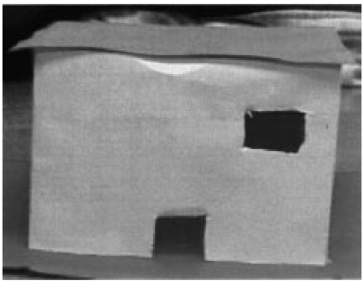


Figure 2. An "early" model structure.

scaled model of 5 m × 3 m × 2.5 m (the students erred in determining the scaled-down dimensions), which are the dimensions of the structure required by the project specification. The roof is flat and the model has two openings: a door and a window. The door's dimensions are barely large enough to let an adult crawl through. No consideration was given to thermal insulation. The roof is unsupported, and laying a mass of 100 g on it (the scaled version of roughly 6,000 kg on a full-size structure, the mass of 2.5 m^3 of sand) caused it to bend inwards markedly and almost collapse.

Figure 3 shows the "late" exemplar model structure built by the same group of students toward the end of the unit. Figure 3a shows the complete model, Figure 3b shows the construction of the walls, and Figure 3c shows the construction of the roof and its supports. The model is made of construction paper, Popsicle sticks, and cotton. The structure is a parallelepiped with an arched roof in order to keep snow and sand from piling on it (this is the reason used by the students to justify their design during their presentation of their model). Initially the students used only four bent beams to support the roof, but when weights were placed on the model, the roof started to cave in (the beams did not lie on top of the vertical walls), so rather than adding other horizontal beams that would be perpendicular to those shown, they added two pillars near the center of the structure (Figure 3c).

The walls are made of vertically placed Popsicle sticks and construction paper, with cotton between them as thermal insulation. When placed inside an ice chest for half an hour, the air temperature inside the structure decreased by only 5°F, even though the initial temperature difference between the air inside and outside the structure was almost 40°F.

Why the sticks were placed on the inside rather than the outside is unclear. The window and door were placed on different walls to allow a breeze to go through the structure. The door can open only outwards so it remains stuck when there is snow or sand piled on the ground. There is no floor, nor is there a description of how the structure would be held in place. The students stated

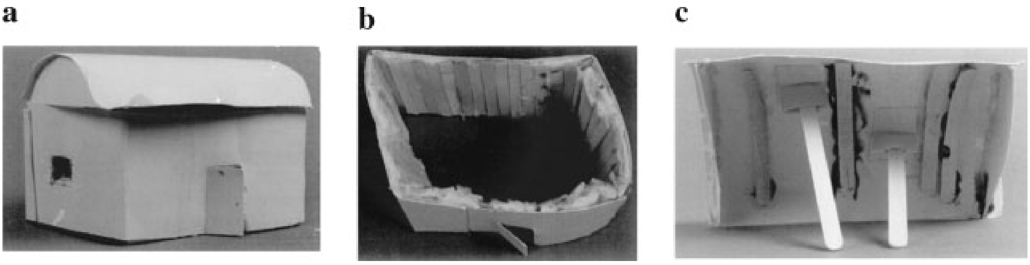


Figure 3. A "late" model structure.

that the outside walls should be painted either white or black, depending whether we wanted to reflect light (desert conditions) or absorb it (arctic conditions).

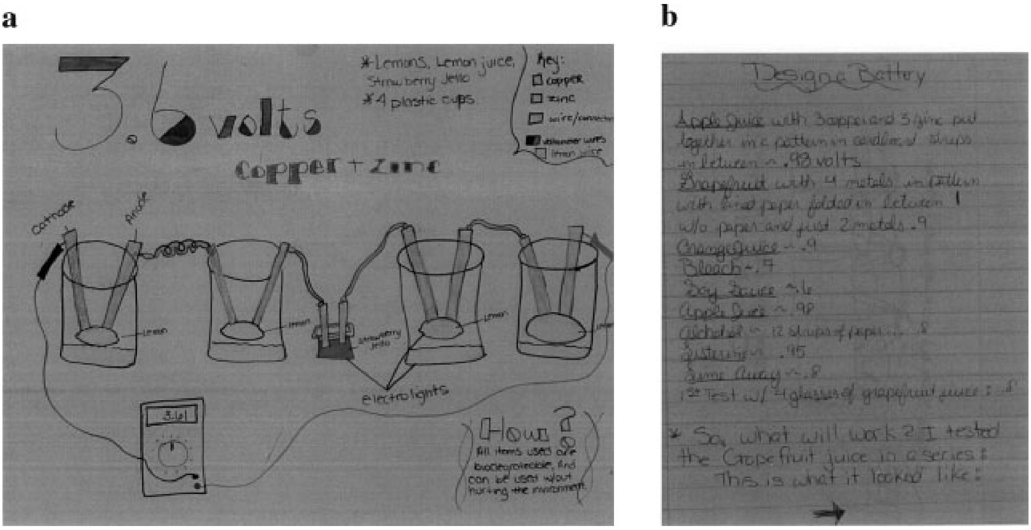
The ‘‘late’’ model and its justification show an application of scientific knowledge that was absent during when the ‘‘early’’ model was built. While some of the scoring criteria could not have been met by the early model (e.g., ‘‘testing’’), the late model was superior to the early model in almost every category. Consideration has been given to particular types of loads to which the structure will be subjected due in extreme environments (the weight of snow and sand on its roof), ways to support these loads, the need to thermally insulate the structure, the different mechanisms of heat transfer, and the need to modify one’s decisions according to the results of tests.

Environmentally Safe Batteries Unit. As was explained earlier, since the students had little previous understanding at the start of the *Environmentally Safe Batteries* unit of how an electrochemical cell is constructed, they designed, constructed, and tested liquid batteries and created posters of their batteries only at the end of the unit.

Seventeen different battery posters were analyzed and scored using the rubric appearing in Table 5, which also presents the mean scores given to these posters and the scores given to an exemplar poster. The mean total score is 10.3 with a SD of 2.1. The following paragraphs describe the exemplar poster in detail. This poster was chosen for detailed description because it scored 12.0, which was within 1 SD above the mean. Thus, it can be considered a good, but representative, example.

Table 5
Battery poster scores

Scoring Criteria: (22 points for all sections)	Exemplar	Mean (SDEV)
General Features (9 points):		
More than a single cell (1)	1	1.0 (0.0)
Cells connected in series rather than in parallel (1)	1	0.9 (0.2)
Correct electrical connections (1)	1	0.8 (0.4)
Anode, cathode, and electrolyte materials (3)	3	2.8 (0.7)
Justification of electrodes and electrolyte (3)	1	0.7 (0.8)
Subtotal	7	6.2 (1.3)
Environmental Safeness (3 points):		
Recyclability and disposability of electrodes and electrolyte (3)	1	1.4 (0.8)
Subtotal	1	1.4 (0.8)
Electric Flow (3 points):		
Intracell flow of ions (1)	0	0.0 (0.0)
Intercell flow of electrons (1)	0	0.1 (0.3)
Correct identification of anode and cathode (1)	1	0.7 (0.5)
Subtotal	1	0.8 (0.6)
Measurements (3 points):		
Measured voltage per cell (1)	0	0.1 (0.2)
Measured voltage for entire battery; greater than 3.2V? (2)	2	1.6 (0.5)
Subtotal	2	1.7 (0.5)
Electric potentials (4 points):		
Anode and cathode electrochemical potentials (2)	0	0.0 (0.0)
Comparison between measured voltage per cell and theoretical voltage (1)	0	0.0 (0.0)
Battery voltage as sum of individual cell voltages (1)	1	0.1 (0.3)
Subtotal	1	0.1 (0.3)
Total	12	10.3 (2.1)



All items used are biodegradable, and can be used w/out hurting the environment.

Design Battery

Apple Juice with 3 copper and 3 zinc put together in a pattern in cardboard strips in between ~ .98 volts
Grapefruit with 4 metals in pattern with [illegible] paper folded in between 1
w/o paper and just 2 metals .9
Orange Juice ~ .9
Bleach ~ .7
Soy Sauce ~ .6
Apple Juice ~ .98
Alchohol ~ 12 strips of paper 8
[illegible] ~ .95
[illegible] ~ .8
1st Test w/ 4 glasses of grapefruit juice : .8

* So, what will work? I tested the Grapefruit juice in a series &
This is what it looked like:
→

Figure 4. A Battery poster and part of its justification.

Figures 4a and b are photos of the exemplar poster and part of the written justification accompanying it that were created by a group of students near the end of the unit. These documents describe a battery actually built and tested at home by a group of students, using metal strips and a multimeter lent to them by the teacher.

The poster shows a liquid battery composed of 5 cells connected in series. The students' goal was to build a battery that supplied at least 3.2 V and was constructed of nontoxic metals and a biodegradable electrolyte. The students chose to use copper and zinc as their electrodes, since the combination of these two metals created the largest potential difference (the students had access to copper, zinc, aluminum, iron, and lead rods). The students found Material Safety Data Sheets (MSDS) on the web showing that under most conditions both copper and zinc were nontoxic and easily disposable.

The students tested a number of different potential electrolytic liquids and decided to use lemon juice. They built four lemon cells and connected them in series. The voltage generated, however was less than the required 3.2 V. The students realized that they needed to add a fifth cell to the battery, but since they had used all the lemons they had, they were forced to use a different electrolyte for the fifth cell. They chose to use strawberry Jell-O. Being digestible organic substances, the electrolytes were clearly biodegradable.

Although the poster mentioned which metal served as the cathode and which served as the anode in each cell, it did not describe the direction of the intracell ionic flow and the inter-cell electron flow. No qualitative portrayal of the chemical reactions taking place inside each cell was made. In theory, by using copper and zinc in each cell, the students should have been able to produce a potential difference approaching 1.1 V per cell; the students did not address why their cells produced much less (0.72 V per cell, on average).

This poster and its justification demonstrate that the students had constructed an understanding of (a) how to build an electric series circuit and the additive nature of electric voltage in such a circuit; (b) how an electrochemical cell's voltage is determined by the difference between its electrode's electrochemical potentials; (c) the concept of evaluating a design by testing its performance; and (d) the need to evaluate several design options before deciding on the preferred one.

Safer Cellular Phones Unit. While the students created cell phone posters at the very start of the unit, the posters focused almost entirely on aesthetic features; only two posters mentioned using an earpiece. Apparently, as the pretest for this unit suggested, the students had very little relevant science knowledge at the start of the unit. For this reason we did not compare early and late version of the cell phone posters. The readers may assume that the scores given to the late cell phone posters and presented below in Table 6 are also gains.

Fourteen different late cell phone posters were analyzed and scored using the rubric appearing in Table 6, which also presents the mean scores given to these posters and the scores given to an exemplar poster. The mean of the total scores is 4.9 with a SD of 1.0. The following paragraphs describe the exemplar poster in detail. This poster was chosen for detailed description because it scored 5.0, which was within 1 SD above the mean, and because it presented a solution that the author considered very creative. Thus, it can be considered a good, but representative example.

Figure 5 portrays the exemplar poster, which includes two versions of a cellular phone created by a group of three students. The original version was created at the end of the first learning cycle; the second version was created near the end of the entire unit. The modifications to the original design are the three additional bullets in green ink, the circle that was attached to the original poster highlighting some safety features, and the attached side note on yellow paper.

Other than the option of listening to the phone with an earpiece, the original phone drawn by the group focused entirely on features that were not safety related. The purpose of the earpiece was to allow the users to hold phone away from their heads. No consideration was given to how the users would speak into the phone if the earpiece came without a mouthpiece, nor to the potential harm that the cell phone's radiation could cause to body parts other than the brain. The shape of the phone was conventional, with an internal antenna.

The final drawing included several safety features, one which demonstrates an impressive understanding that the intensity of radiation decreases as the distance from radiation's source increases. This feature appears on the yellow side note and is worded as follows: "If you were to add more towers around the area, you can reduce the amount of power used than a cell phone and

Table 6
Late cellular phone poster scores

Scoring Criteria: (12 points for all sections)	Exemplar	Mean (SDEV)
Radiation Safety (6 points):		
Antenna pointing away (1)	1	0.7 (0.5)
Hip mounted unit (1)	1	1.0 (0.0)
Extendable antenna (1)	1	0.7 (0.5)
Multiple antennas (1)	0	0.0 (0.0)
Radiation shields (1)	0	0.3 (0.5)
Smaller cell size (1)	1	0.2 (0.4)
Subtotal	4	2.9 (1.1)
Sound Safety (6 points):		
Limiting output volume (1)	1	0.7 (0.5)
Decibel meter (1)	0	0.0 (0.0)
Adaptable volume (1)	0	0.6 (0.5)
Microphone and earphone filters (2)	0	0.6 (0.5)
Warning tone (1)	0	0.1 (0.3)
Subtotal	1	2.0 (0.8)
Total	5	4.9 (1.0)

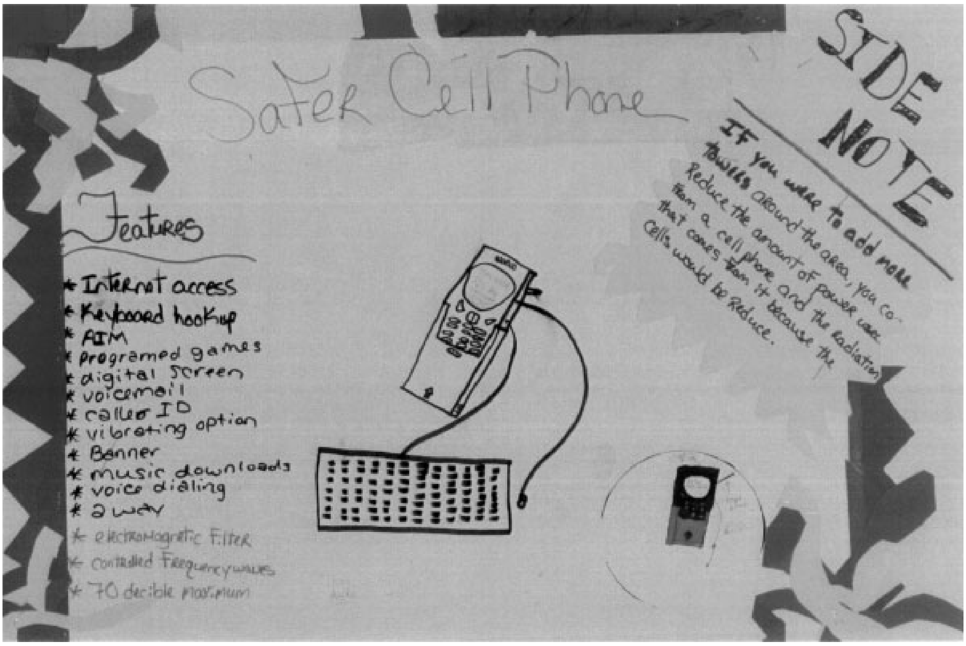


Figure 5. A cellular phone poster.

the radiation that comes from it because the cells would be reduce." The intensity at which a cell phone radiates is determined by the distance between it and the nearest cell phone tower: the nearer the tower, the weaker the radiation emitted. Thus, instead of embellishing the cell phone with radiation-reducing features, by increasing the number of cell phone towers, the typical distance between the cell phone and the towers is reduced, allowing the cell phone to emit a weaker signal.

Other new safety features included a 70-dB limit on the sound intensity in order to prevent hearing damage (appears on the poster in green ink) and an external antenna that points away from the user (in the attached circle).

In summary, the analyses of the artifacts created by the students during all three unit enactments demonstrate that at the end of each unit the students had substantial science knowledge that they were able to apply to the solution of design problems.

Discussion

National organizations have recommended using inquiry-based science frameworks in order to help students develop the knowledge and skills necessary in a science and technology rich world (Bartel et al., 1992; Lipman, 1991; NRC, 1996). The process of reforming the educational system to meet these new recommendations is difficult and complex. This reform effort must address several issues related to the organizational culture of schools, the capability of the educators involved in terms of their understandings and expertise, and the policy and management structure concerns of the school system being affected (Blumenfeld, Fishman, Krajcik, Marx, & Soloway, 2000). To justify these reform efforts, it must first be shown that various inquiry-based science classrooms foster the construction of significant science knowledge, and that this knowledge transfers to extra-classroom settings. Many inquiry-based programs already exist (Kolodner et al., 1998; Krajcik, Czerniak, & Berger, 2003; Linn, 1997; Songer, Lee, & Kam, 2002). This study attempts to add support to the use of inquiry-based curricula by providing a detailed description of a particular inquiry-based science program called DBS, as called for by Anderson and Hogan (1999). Researchers and national and international organizations have recognized the relevance of design to the reform movement and have recommended incorporating design activities into school science (AAAS, 1990; Chiapetta et al., 2002; Davis, 1998; ITEA, 2002; Kimbell et al., 1996; Layton, 1993; NRC, 2002). However, there are not many design-based science programs.

As with other inquiry-based programs, the process of developing DBS curricula and of supporting teachers as they began to develop the expertise required to successfully implement the curricula was long and arduous (Mamlok et al., 2001). Design-based teaching may be particularly difficult for teachers as it deals with *how* questions rather than with the *why* or *what* questions, which are typically found in traditional curricula. In DBS, there are many answers to the *how* questions, many design solutions that can meet the design specifications; some may be better and some worse, but many can be acceptable responses. It can be very difficult for the teacher to know in advance what form the design solution of a group will take (Fasse, Gray, Holbrook, Camp, & Ryan, 2001). This is in marked contrast to other pedagogies that are driven by *why* or *what* driving questions, where there is probably a single answer to the question that could be acceptable to both the students and to a group of experts; perhaps the teacher knows this answer in advance, or at least knows how to find it. On the other hand, the existence of this multitude of ‘‘appropriate’’ responses in DBS unit may help teachers relinquish their traditional role of knowledge imparters. This potential difficult in teaching DBS units needs to be considered in future studies which should also look at closely at the teachers’ perspectives, their knowledge and experiences, how they adapt DBS curricula, and what kind of support they provide their students.

Because it is centered on student-created models, DBS can lead to a sense of personal ownership among the students. Throughout each unit, the students create, modify, and improve their models. As the models grow, so does the students’ science knowledge. By comparison, in Project-Based Science (Krajcik et al., 2003), another inquiry-based science pedagogy, the final goal of a unit is to generate a collective answer to a driving question. Thus, Project-Based Science can lead to a more communal sense of ownership. Both types of ownership, personal and communal, can be strong motivators, depending on the students’ personal attitudes (Pintrich & Schunk, 1995).

In some sense, the design goal in DBS can be viewed as setting up a competition in which the students compete, not with each other, but with the design specification. A design goal like ‘‘Can you design a cell phone that is safer to use?’’ sets a challenge, dares the students to test their skills and their knowledge and see if they can design a cell phone that fulfills all of the specification’s requirements. Like ownership, a sense of challenge can be a powerful motivator (Pintrich & Schunk, 1995). However, it can also deter some students.

As demonstrated by the tests and artifacts described earlier, substantial science learning occurred in both high-achieving and low-achieving students during all three DBS enactments. On the other hand, the question whether the knowledge that was constructed is ‘‘good enough’’ is open to debate. The mean scores on the posttests were 15, 12, and 11 while the maximum possible scores were 23, 22, and 21. By design, in order to avoid a ceiling effect, there were a number of intentionally challenging items on each test. Likewise, the mean scores given to the artifacts were 11, 10, and 5 out of 20, 22, and 12, respectively. Perhaps our scoring rubrics were too demanding? There were several criteria to which no student responded and even more to which only few responded correctly. Or perhaps DBS is not an ‘‘efficient’’ learning environment? This question can be answered only by comparing DBS with other pedagogies that focus on identical learning goals.

Because this study made no use of a control group, it is impossible to demonstrate that the knowledge constructed by the students was due to the DBS units. However, given the nature of the knowledge that was assessed and the fact that the students had very little understanding of these concepts before the enactments and after 10 years of schooling, it seems unlikely that the students happened to construct the knowledge assessed by the tests during the few weeks the enactments lasted but in environments other than that created by the DBS enactments. We feel, therefore, that it is reasonable to assume that this knowledge was constructed due to the students' participation in the DBS enactments.

With DBS, our goal was to support the construction, not only of science knowledge, but also of designerly skills, which are, as mentioned earlier, a type of problem-solving skills. An authentic evaluation of these skills has to be based on performance assessments, not static assessments such as the pre-/posttests used in this study. While the process of creating and modifying the artifacts described in this study might have provided insight into the development of these designerly skills, the process was strongly supported by its dependency on the learning cycle—the students knew what the purpose of every activity was and what was expected of them. Thus, they knew when they had to test, when they had to gather information, and so on. On the other hand, they were not guided in how to incorporate their science understanding in their designs. For example, while the students were prompted to justify their decisions, they were not told which science concepts were relevant to their justifications. Thus, the instruments used in this study were not suited to evaluate the development of designerly skills.

Even if one accepts that the learning environment described in this study supported the construction of substantial knowledge, the question remains whether it also fostered the student's ability to apply this knowledge to new real-world contexts. That, in the end, is the ultimate test of any learning environment. Therefore, one of the next steps in justifying the development of DBS must be to assess the students' ability to transfer this learning to the solution of new problems in extra-classroom settings.

Appendix A: Alignment With National and State Standards

NRC Standards	Michigan Standards
Structures	
Content Standards A & E	Content Strand I
1. Identify questions that guide scientific investigation/Identify a problem	1. Gather and synthesize information from books and other sources of information
2. Design and conduct scientific investigations/Propose designs, choose between alternative solutions, and implement a proposed solution	2. Discuss topics in groups by being able to restate or summarize what others have said, and take an alternative perspective
3. Use technology and mathematics to improve investigations and communications	3. Recognize and explain the limitations of measuring devices
4. Evaluate a solution and its consequences	
5. Communicate and defend a scientific argument/Communicate the problem, process, and solution	
Content Standard B	Content Strand II
1. Most observable forces such as those exerted by a coiled spring or friction may be traced to electric forces acting between atoms and molecules	1. Describe the advantages and risks of new technologies
2. Energy can be transferred by collisions in chemical and nuclear reactions, by light waves and other radiations, an in many other ways	2. Justify plans or explanations on a theoretical or empirical basis

Appendix A: (*Continued*)

NRC Standards	Michigan Standards
3. Heat consists of random motion and the vibrations of atoms, molecules, and ions The higher the temperature, the greater the atomic or molecular motion	3. Show how common themes of science, mathematics, and technology apply in real-world contexts
	Content Strand IV
	1. Describe and compare objects in terms of mass, volume, and density
	2. Describe that when one objects exerts a force on a second object, the second object exerts an equal and opposite force on the first object
	3. Analyze the operation of machines in terms of force and motion
	4. Explain changes in matter and energy involving heat transfer
	Content Strand V
	1. Explain the relationship between the hydrosphere, regional climates, and human activities
	2. Explain and predict general weather patterns
Batteries	
Content Standards A & E	Content Strand 1
1. Identify questions that guide scientific investigation/Identify a problem	1. Gather and synthesize information from books and other sources of information
2. Design and conduct scientific investigations/Propose designs, choose between alternative solutions, and implement a proposed solution	2. Discuss topics in groups by being able to restate or summarize what others have said, and take an alternative perspective
3. Use technology and mathematics to improve investigations and communications	3. Design and conduct simple investigations
4. Evaluate a solution and its consequences.	
5. Communicate and defend a scientific argument/Communicate the problem, process, and solution	
Content Standard B	Content Strand II
1. Matter is made of minute particles called atoms, and atoms are composed of even smaller components. Each atom has a positively charged nucleus surrounded be negatively charged electrons	1. Describe the advantages and risks of new technologies
2. The electric force is a universal force that exists between any two charged objects. Opposite charges attract while like charges repel	2. Justify plans or explanations on a theoretical or empirical basis
3. Chemical reactions may release or consume energy	3. Show how common themes of science, mathematics, and technology apply in real-world contexts
4. In some materials, such as metals, electrons flow easily, whereas in insulating materials such as glass they can hardly flow at all	
Content Standard F	Content Strand III
1. Materials from human societies affect both physical and chemical cycles of the earth	1. Describe and explain the structural parts and electrical charges of atoms
2. Human-induced hazards present the need for humans to assess potential danger and risk. Many changes in the environment designed by humans bring benefits to society, as well as cause risks	2. Describe how common forms of energy can be converted one to another
	3. Describe electron flow in simple electrical circuits
	4. Construct and explain simple circuits using wires, light bulbs, fuses, switches, and power sources

Appendix A: (*Continued*)

NRC Standards	Michigan Standards
	Content Strand IV
	1. Describe how common materials are made and disposed of or recycled.
	2. Describe common chemical changes in terms of properties of reactants and products.
	3. Explain chemical changes in terms of the arrangement and motion of atoms and molecules.
Cellphones	
Content Standards A & E	Content Strand 1
1. Identify questions that guide scientific investigation/Identify a problem.	1. Gather and synthesize information from books and other sources of information.
2. Design and conduct scientific investigations/Propose designs, choose between alternative solutions, and implement a proposed solution.	2. Discuss topics in groups by being able to restate or summarize what others have said, and take an alternative perspective.
3. Use technology and mathematics to improve investigations and communications.	3. Investigate toys/simple appliances and explain how they work.
4. Evaluate a solution and its consequences.	4. Design and conduct simple investigations.
5. Communicate and defend a scientific argument/Communicate the problem, process, and solution.	
Content Standard B	Content Strand II
1. Solid, liquids, and gases differ in the distances and angles between molecules or atoms. In solids the structure is nearly rigid; in gases molecules or atoms move almost independently of each other and are mostly far apart.	1. Describe the advantages and risks of new technologies.
2. Most observable forces such as those exerted by a coiled spring or friction may be traced to electric forces acting between atoms and molecules.	2. Justify plans or explanations on a theoretical or empirical basis.
3. The electric force is a universal force that exists between any two charged objects.	3. Show how common themes of science, mathematics, and technology apply in real-world contexts.
4. Waves, including sound and seismic waves, waves on water, and light waves, have energy and can transfer energy when they interact with matter.	
Electromagnetic waves result when a charged object is accelerated or decelerated. Electromagnetic waves include radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, x-rays, and gamma rays.	
Content Standard F	Content Strand IV
1. Natural and human-induced hazards present the need for humans to assess potential damage and risk. Many changes in the environment designed by humans bring benefits to society, as well as cause risks.	1. Explain how sound travels though different media.
2. Science and technology are essential social enterprises, but alone they can only indicate what can happen, not what should happen	2. Relate characteristics of sound that we hear to properties of sound waves.
	3. Explain how sound recording and reproduction devices work.
	4. Describe different types of waves and their technological applications.
	5. Describe waves in terms of their properties (frequency, amplitude, wavelength, and wave velocity).
	6. Explain how objects or media reflect, refract, transmit, or absorb light.
	7. Explain how waves transmit energy.

Appendix B: Science Content Tests: Sample Items

Structures for Extreme Environments

1. Which of the following weather conditions are typical of the interior of Antarctica?

   A. Freezing temperatures, low precipitation levels, and high wind speeds.
   B. Freezing temperatures, high precipitation levels, and high wind speeds.
   C. Freezing temperatures, low precipitation levels, and no wind.
   D. Freezing temperatures, high precipitation levels, and no wind.

2. The floor plan of a house is drawn with a scale of 1:50. Using a ruler, an architect measures the dimensions of a rectangular room in the house and gets 12 cm × 8 cm. What is the actual area of the full-sized room?

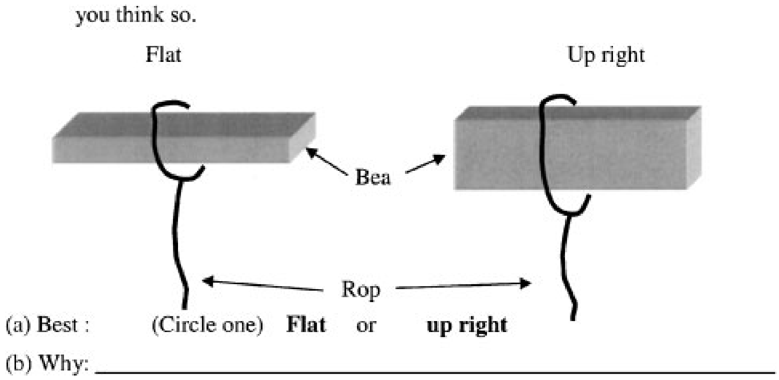
   A. 12 cm × 400 cm
   B. 600 cm × 8 cm
   C. 600 cm × 400 cm
   D. 1.2 cm × 0.8 cm

3. The following table gives the masses for different volumes of different substances. Which substance has the smallest density?

	Mass	Volume
	(g)	(cm^3)
Block of aluminum	725	268
Beaker of water	1,000	1,000
Bar of iron	1,000	128
Cube of ice	917	1,000

   A. Aluminum.
   B. Water.
   C. Iron.
   D. Ice.

4. A carpenter is working on a tire swing in a city park. You notice that is getting ready to place the wood support beam that will hold the rope for the tire swing. The carpenter has two ways to place the beam. State which way will work the best and describe why you think so.



(a) Best : (Circle one) **Flat** or **up right**

(b) Why: ____________________

5. Why would tightly closed windows be a good design choice in cold climates but not a Anigloo is a structure that is used for survival in extremely cold environments with snowstorms. The structure is typically made of blocks of ice laid one on another in order to form the shape of a dome.

   (a) Describe how you would test this structure to evaluate its ability to withstand static and dynamic forces:

   ____

   (b) Describe how you would test this structure to evaluate its thermal insulation:

   ____

Environmentally Safe Batteries

1. When the compound copper chloride is dissolved in water, it dissociates into positive copper ions and negative chloride ions. The resultant solution conducts electricity. The reason for the electric conductivity is that:

   A. molecules of copper chloride can migrate to charged electrodes.
   B. copper ions and chloride ions combine to form molecules.
   C. copper ions and chlorine ions can migrate to charged electrodes.
   D. the copper's electrons are able to move in the solution toward the electrodes.

2. In order to produce electricity from a battery, the electrodes of the battery must:

   A. have an electrochemical potential difference.
   B. both be liquids.
   C. be exposed to light.
   D. be at two different temperatures.

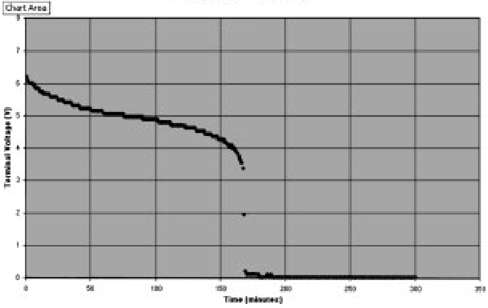
3. From an environmental point of view, why are NiMH batteries preferable to NiCad batteries?

   A. They take up less space in landfills.
   B. They can be recharged. C. They contain materials that are not as toxic.
   D. They do not use an electrolyte.

4. Which is true for the following circuit?

   A. The current flowing through the battery is identical to the current flowing through each of the lamps.
   B. The voltage between points 1 and 2 is zero.
   C. The lamps have no resistance.
   D. The voltage between points 3 and 4 is identical to the voltage between points 5 and 6.

5. The following shows a discharge curve of a battery.



(1) Using the words such as ‘‘decrease’’, ‘‘increase’’, ‘‘quickly’’, ‘‘slowly’’, ‘‘suddenly’’ and ‘‘zero’’, describe the relation between voltage and time in this graph. There should be three parts to your description.

(2) What were the battery’s initial and final voltages?

Initial: ____________________

Final: ____________________

(3) Using the graph, estimate how much time went by until the battery gave only half of its initial voltage.

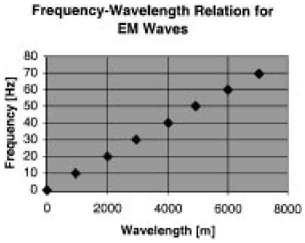
(4) A personal computer works with voltages that are greater than 5.5V, but cannot work with voltages that are less than 5.5V. Would you choose this battery for operating your personal computer?

I Yes _____ No _____

II Explain.

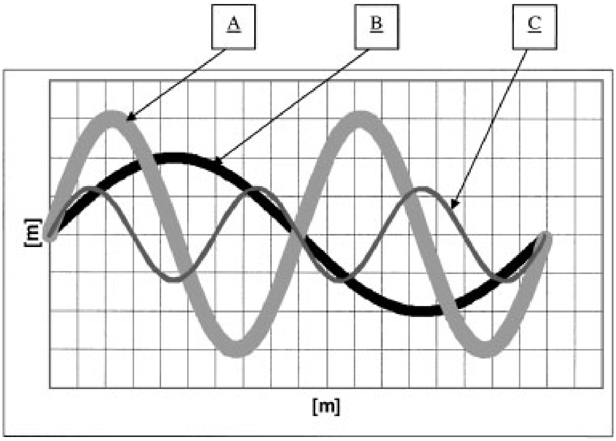
Safer Cellular Phones

1. Which of the following is *not* transverse wave?
   - A. a plucked guitar string.
   - B. a surface wave on a pond of water.
   - C. a sound wave.
   - D. X-Rays.
2. Which of the following EM wavelengths has the highest frequency?
   - A. meter.
   - B. meter.
   - C. 10 meters.
   - D. 100 meters.
3. The intensity of sound waves
   - A. decreases as the distance from the sound source increases.
   - B. increases as the wavelength increases
   - C. decreases the longer we wait to measure it
   - D. increases as the distance from the sound source increases.



4. What is wrong with this graph?
   - A. the frequency and wavelength of EM waves are related differently than depicted in the graph.
   - B. the units on the vertical axis are wrong.
   - C. the units on the horizontal axis are wrong.
   - D. there is no relation between the frequency and wavelength of EM waves.
5. A slinky was held at one end and shaken back and forth at the other end in order to produce periodic transverse waves in it. Each time it was shaken with a different frequency and amplitude. The graph below shows the three different waves (A, B, and C) that were generated. Which of the three waves has the:

A.	lowest frequency	A	B	C
B.	smallest wavelength	A	B	C
C.	smallest amplitude	A	B	C



6. When you put food in a microwave oven, it heats up rapidly. On the other hand, when you hold an operating cellphone next to your head, your head barely warms at all. Give two reasons for this.

Appendix C: Structures for Extreme Environments: Scoring Rubric for Open-Ended Items

16.	(a)	Up right	_____
	(b)	An upright beam bends less.	_____
17.	Cold climates:		
	a.	The air outside is colder than inside, or, The air inside is warmer than outside.	_____
	b.	Opening windows lets outside air in (undesirable).	_____
	Hot climates: Either...		
	a.	The air outside is colder than inside, or, The air inside is warmer than outside.	_____
	b.	Opening windows lets outside air in (desirable).	_____
	or...		
	c.	A breeze cools our body by increasing the rate of evaporation of our perspiration.	_____
	d.	Opening windows can create a breeze.	_____
18.	Either...		
	(a)	Design #1	_____
	(b)	Design #1 has a firm foundation, or, Design #1 will not roll away.	_____
	(c)	Its walls and roof should be rounded to minimize air drag, or, Its roof should be rounded or slanted in order to allow snow and sand to fall off.	_____
	or...		
	(a)	Design #2	_____
	(b)	Design #2 allows snow and sand to fall off the roof.	_____
	(d)	Its base should be flattened to give it a better foundation so that it will not roll away.	_____
	In either option, give no points for (a) If (be) Is not correct.		
19.	(a)	For static forces either... Put increasing weights on it and measure its deformation	
Or...			
		Put increasing weights on until it collapses.	_____
		For dynamic forces, put it in a very windy environment and see if it sways or collapses.	_____
	(b)	First heat the air inside the igloo then turn off the source of heat measure the air temperature inside at different intervals.	_____

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