Design-Based Science (DBS) and Real-World Problem-Solving

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International journal of Science Education (In press)

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Abstract

Design-Based Science (DBS) is a science pedagogy in which new scientific knowledge and problem-solving skills are constructed in the context of designing artifacts. This paper examines whether the enactment of a DBS unit supported students' efforts to construct and transfer new science knowledge and 'designerly' (Baynes, 1994) problem-solving skills to the solution of a new real-world design problem in a real-world setting. 149 students participated in the enactment of a DBS unit. Their understanding of the curricular content was assessed by identical pre- and post-instructional written tests. They were then given a new design problem as a transfer task. There was a statistically significant increase on scores from pre- to post-test with an effect size of 1.8. There was a stronger correlation between the scores of the transfer task and those of the post-test than with those of the pre-test; we use this finding to suggest that the knowledge that was constructed during the unit enactment supported the solution of the transfer task. This has implications for the development of science curricula that aim to lead to the construction of knowledge and skills that may be useful in extra-classroom settings. Whether participation in consecutive enactments of different DBS units increases transfer remains to be investigated in more depth.

Introduction

Most real-world problems are ill-defined to some degree, lacking required information, and not having a well-defined ending state and therefore with neither a known correct nor best solution (Frederiksen, 1986; Glass, Holyoak, & Santa, 1979; Nickerson, 1994; Reitman, 1964; Roberts, 1995). Examples of ill-defined, real-world problems include what to do for your child's birthday party, how to ensure that you will have a continuous and plentiful supply of drinking water, and how to build a cellular phone that minimizes the radiation absorbed by your brain.

School science has been traditionally built around well-defined problems, such as predicting an ideal projectile's trajectory or calculating how much hydrogen is released by the decomposition of a given amount of water. On the other hand, real-world scientific inquiry focuses on ill-defined problems, as aptly described by AAAS (1990): "There simply is no fixed set of steps that scientists always follow, no one path that leads them unerringly to scientific knowledge" (p. 4).

Many school curricula and teaching practices have been criticized because their academicism does not give students experience in real-world problems, in situations where decisions are not clear-cut, where requirements can conflict, where optimization rather than 'proof' is needed. These situations have been called ”indeterminate zones of practice" (Schön, 1987, p. 6). Several researchers have recommended restructuring school science around real-world issues relevant to the students' lives, using pedagogical frameworks that will help the students develop the knowledge and skills necessary in a science and technology rich world (AAAS, 1990; Bartel, Lichtenberg, & Vaughan, 1992; Blumenfeld et al., 1991; Lipman, 1991).

Following these recommendations, several K-12 science programs that stress inquiry have been developed (CTGV, 1992; Krajcik et al., 1998; Linn, 1997; Penner, Lehrer, & Schauble, 1998; Songer, 1996). Many of these programs are founded on the assumption that learning occurs best when the students are engaged in finding solutions to real-world problems. Evidence gathered from these 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), do not consider evidence systematically in formulating arguments (Linn, 1992), and are proficient at carrying out procedures but have difficulty focusing their attention on the reasons for these procedures (Krajcik et al., 1998).

Although inquiry-based curricula and teaching practices give students experience in dealing with real-world problems, it is not yet evident whether the activities in inquiry-oriented classrooms help students construct knowledge that will help them deal with real-world problems while working in real-world settings. Although transfer has been hotly debated in the education literature (Bassok & Holyoak, 1993; Bransford & Schwartz, 1999; Brown & Kane, 1988; Detterman, 1993), undeniably the goals of science education must include the transfer of learning from academic settings into students' lives outside of school. If the knowledge and skills being constructed by students in classrooms do not transfer or support their problem-solving efforts in extra-classroom settings, the goal of helping students develop the knowledge and skills necessary in a science and technology-rich world is not being met.

Our response to the potential problem of limited transfer of learning from school science to everyday settings is Design-Based Science (DBS), an inquiry-based science pedagogy in which new scientific knowledge and problem-solving skills are constructed in the context of designing artifacts. This paper examines whether the enactment of a DBS unit supported students' efforts to construct and transfer new science knowledge and 'designerly' (Baynes, 1994) problem-solving skills to the solution of a new real-world design problem in a real-world setting.

Design-Based Science (DBS) Curricula

Using Design in Science Education

We have developed three ninth grade inquiry-based science units that can serve as a context to explore whether inquiry-base science curricula can foster the construction and transfer of particular skills that may be useful at solving certain real-world science problems. The units are structured around *design problems,* incorporate the explicit goal of meeting state and US national curriculum standards (Michigan Department of Education, 1996; National Research Council, 1996), and utilize artifacts available at the Henry Ford Museum in Dearborn, Michigan (Fortus, Dershimer, Krajcik, Marx, & Mamlok, 2002).

One of the goals of these units was to promote the development of skills that may be useful in a wide range of real-world problem-solving situations involving science. Design, which can be viewed as a method for dealing with science-related real-world problems

(Davis, Hawley, McMullan, & Spilka, 1997), was the organizing principle we chose. Design is an indeterminate zone of practice; the problems it deals with are ill-defined in a number of aspects (Simon, 1973), with no prescribed path leading from the requirement specification to the final design product (Bucciarelli, 1994). Often there are no well-defined criteria how to evaluate a design solution, so there is no clear definition of when an acceptable solution has been reached. Even when such criteria are available, 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 (Layton, 1993). It must, however, be an acceptable answer to the requirements.

Everyone naturally engages in problem solving (Nickerson, 1994). The same is true for design activities. 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; it is not the possession of a gifted few (Roberts, 1995). Indeed, it has been shown that 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 of all students.

The pedagogy that resulted from our efforts to orchestrate the construction of new scientific knowledge around design activities, called design-based science (DBS), focuses on helping students construct new 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 design experiences lie at the heart of the DBS materials. All new scientific knowledge and problem-solving skills are constructed in the context of designing artifacts as particular instances of solving ill-defined, real-world problems.

While this study focuses on a ninth grade science unit called *How do I Design a Structure for Extreme Environments?*, which deals with weather conditions, technical drawings, different sources of loads, structural integrity, and thermal insulation, two additional units were developed: *How do I Design a Battery that is Better for the Environment?* and *How do I Design a Cellular Phone that is Safer to Use?* All three units were structured around a *design goal* chosen to be interesting and challenging to the students.

Each DBS unit begins with the presentation of a *design specification*. This specification includes the exact requirements the students' models are expected to fulfill, and how the fulfillment of these requirements will be assessed. Thus, the students know what the curriculum is about, what is expected of them and how their artifacts will be evaluated.

A number of design-based science curricula have been described in the science education and cognitive science literatures. Most are middle school or elementary grades curricula. For example, there is a middle school program called *Learning By Design*™ (Puntambekar & Kolodner, 1998) is based on a conceptual framework taken from case-based reasoning (Kolodner, 1993) and classroom practices taken from problem-based learning (Barrows, 1985). Two other groups have focused their interest on the development of models by students in elementary-schools and on the importance of these artifacts in the learning process (Penner et al., 1998; Roth, 1996); a third group (Kafai & Ching, 1998) studies computer software design as an environment for promoting student-directed scientific inquiry.

The idea of combining science and design in classrooms has received much attention in the United Kingdom. The 1988 Education Reform Act (Association for Science Education, 1988) established technology as one of the ten subjects in the National Curriculum for all children aged 5-16 in state-maintained schools. Technology is defined there "as that area of the curriculum in which pupils design and make useful objects or systems" (p. 20). It is assumed "that pupils will draw on knowledge and skills from a range of subject areas, but always involving science or mathematics" (Layton, 1993). Rather than use design as a vehicle to support the learning of science, the British have chosen to use science as a resource to be used in design.

The DBS Learning Cycle

One of the characteristics that set DBS apart from these other curricula is its cyclic nature. Each unit is organized around a learning cycle as described in Figure 1.

Insert Figure 1

Each cycle lasts approximately one week. In order to acquaint students with the stages in the design process, a cycle is usually completed in a linear and 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 non-linear process. The main purpose of the cycle is to engage students in a design process without having to spend time explicitly teaching them about design (Mamlok, Dershimer, Fortus, Krajcik, & Marx, 2001). While teaching and learning design is a very useful activity (Davis et al., 1997) it is not a requirement of the national or state science standards (Michigan Department of Education, 1996; National Research Council, 1996). Each cycle focuses on a different aspect of the design problem. The cycle is presented to the students near the start of each unit. Later it is mentioned at the start of each lesson, with the teacher pointing out how the day's activities fit in the cycle.

The first stage in each cycle is contextualization. Design problems that are significant to the learners can improve their learning of abstract arguments (Wason & Johnson-Laird, 1972). Context also 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).

The second stage of background research can be in the form of searching and gathering relevant information, benchmark lessons in which the teacher presents new scientific concepts, reading selected materials, 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 virtual expeditions to examine appropriate primary sources.

Group problem-solving can enhance student learning (Evans, 1989; Sharan & Sharan, 1989), so we have included small group work into DBS. In the third stage every student generates their solution to the design problem and presents it to their group members. The group decides which of the suggested solutions they prefer or they might combine the solutions. The group then writes a justification for their decision.

In the fourth stage, each design team constructs a model or modifies an existing model based upon the design solution they decided upon in the former stage. For example, they might construct a 3D model of a house or a cellphone antenna shield, or a cut-away drawing of an electrochemical cell.

In the final stage, students' models are subjected to physical tests whenever possible, and they are presented to the entire class in a pin-up session (Kolodner et al., 1998; Schön, 1985). 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 with their own critique.

Transfer Promoting Features

The second main characteristic that sets DBS apart from other inquiry-based curricula is its explicit incorporation of several features that have been shown to enhance transfer. The first is the presentation of concepts in multiple contexts. Contextualization enhances initial learning because it helps the students appreciate the relevance of new information; however, it can impede transfer because the knowledge may be tied too closely to the original context (Bjork & Richardson-Klavhen, 1989; Gick & Holyoak, 1980). By teaching a subject in multiple contexts, there is a greater chance that 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. For example, the concept of heat transfer is discussed and explained in the contexts of an arctic igloo, a cup of hot chocolate, the mixing of hot and cold water, and a desert shelter.

The second transfer enhancing feature is the fostering of learning for understanding (Brown & Kane, 1988; Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, de Leeuw, Chiu, & Lavancher, 1994; Chi, Slotta, & de Leeuw, 1994). The likelihood of transfer is largely dependent on the type of representations constructed (Wertheimer, 1945). *Meaningful learning* (Katona, 1940), which occurs when an understanding of the structural relations within a problem develops, leads to the construction of generalizable representations that can be mapped or transposed onto new problem situations, thus promoting transfer. For example, when discussing heat conduction and heat convection in a cup of hot chocolate, the students learn not only about the phenomena and its characteristics, but also the molecular explanation for these phenomena. This understanding helps the students understand how these concepts are relevant and applicable to the context of an arctic shelter.

The third transfer enhancing feature is the introduction of information to be learned in the context of solving problems rather than just as simple facts (Adams et al., 1988; Lockhart, Lamon, & Gick, 1988; Michael, Klee, & Bransford, 1993). The unit is completely contextualized by problems: The problem of designing a structure for extreme environments and its sub-problems: How much weight is on the roof, how can this weight be supported, how cold or hot does the structure get, and so on. This manner of instruction promotes students' *sagacity* (James, 1890) by focusing their attention on the pragmatic aspects of the issue at hand that are relevant to its later application.

The fourth transfer-enhancing feature incorporated in the curricula is the emphasis given to metacognition, which has shown to increase transfer by enhancing students' awareness of their own knowledge and learning strategies. Metacognitive students identify and clarify those aspects of new material that may be relevant for future use (Palincsar &

Brown, 1984; White & Frederiksen, 1998). In the unit's worksheets students are repeatedly requested to reflect on the results they obtained in an activity or the response they crafted to a question and how they hope this may assist them with the problem they are presently facing, such as designing thermal insulation or the shape of a ceiling.

Bransford and Schwartz (1999) argue "that evidence of transfer is often difficult to find because we tend to think about it from a perspective that blinds us to its presence" (p. 66). They claim that transfer was traditionally characterized as the capacity to apply prior learning directly to a new problem or new setting. Most transfer research was based on "sequestered problem solving" (SPS) where the subjects were sequestered during the tests of transfer in order to prevent them from possible exposure to "contaminating" information. Bransford and Schwartz prefer to shift the focus of transfer to the "preparation for future learning" (PFL), that is, to the ability to learn in knowledge-rich environments. They feel that success in solving future problems is dependent not only on formerly constructed knowledge, but also on the ability to gather relevant information and construct new knowledge. Traditional SPS transfer studies may be too brief and the participants may be too isolated from sources of information in order to find evidence of transfer.

The PFL perspective is consistent with the educational goal of helping students develop the knowledge and skills necessary in a science and technology rich world. This is a world in which more than ever before, due to rapidly changing conditions, people need to be able to learn new skills quickly (Jones & Idol, 1990; Kasarda, 1988; Secretary's Commission on Achieving Necessary Skills, 1992, April).

The PFL perspective led us to include an explicit "background research" step in the DBS learning cycle, in which students may be confronted with problems (such as determining the weather conditions in an arctic blizzard) that require them to gather new information and determine its relevancy to the problem at hand.

Research Question

The purpose of this study is to examine whether enactments of the *How Do I Design a Structure for Extreme Environmental Conditions?* unit supported students' efforts to construct and transfer new scientific knowledge and 'designerly' skills to the solution of a new real-world science-related problem in a real-world setting.

We define scientific knowledge as that knowledge whose construction was assessed by identical pre- and post-instructional written tests. 'Designerly' problem-solving skills are the ability to implement the steps of the DBS design cycle in solving a science-related design problem. A real-world setting is one in which students have unlimited, but unsupported access to their peers, friends, family, and any type of information they deem relevant.

Method

Setting and Participants

This study was conducted in six ninth and tenth grade integrated and physical science classes taught by two teachers at the single public high school of a small industrial town located near Detroit, MI, USA during the 2000-2001 school year. The teachers had no extra help in the classrooms. The unit was planned to span eight weeks, but lasted 11 weeks.

One of the teachers had two years experience teaching full-time, having taught night and summer classes in the past. He had a BS in earth science education with a minor in geography. He was certified to teach secondary earth, physical and integrated science, geography, history, government, and economics. He taught four of the six classes that participated in the study. The other teacher had six years experience, five and a half in high schools and half a year in a middle school. She had a BS in biology with a minor in general science and a master's degree in educational administration. She was certified to teach biology, life science and physical science in grades 7-12. Neither teacher had any former experience using inquiry-based curriculum. Both teachers were chosen by the school's principal to participate in the curricula enactments; both participated in a number of curricular support sessions during the school year.

In all, 149 ninth and tenth grade students in four integrated science and two physical science classes participated in the curriculum enactment; 87% of the students were white, 10% were Hispanic, 2% were Black, 1% were Asian, and less than 1% were Native American. Almost all the students came from blue-collar working families; 13% were entitled to free or reduced price lunch. There was a 5% turnover during the school year. As specified by the curriculum, the teachers allowed the students in all classes to form self-selected groups of four.

Procedure

The study commenced by administering a pre-instruction content knowledge test, which was immediately followed by enactments of the *How Do I Design a Structure for Extreme Environmental Conditions?* unit in its entirety. The researchers were present in the classes only during those activities that the teachers felt uncomfortable doing the first time on their own. The unit's enactments ended with a post-instruction test, which served as a final exam. A transfer task was then administered on the three days that followed the post-test. One of the researchers replaced the teacher as the class leader during the transfer task. Each day after class, the researcher wrote a summary of his impressions of that day's activities.

Instruments

Classic transfer tests have traditionally been done by comparing the performance of participants on identical or very similar pre-and posttests, with an intervention not specifically designed to improve performance on these tests (Thorndike & Woodworth, 1901; Woodrow, 1927). In cases where studies included a control group, this was done in order to verify that the participants' performance was not improving due to test-repetition or participant maturation (De Corte, 2002; Hendrickson & Schroeder, 1941; Judd, 1908). Comparison groups have been used to provide evidence for the efficacy of the treatment. When studies were not intended to identify the cause of transfer, but only to verify that it did or did not occur (Brown & Kane, 1988; Reed, Ernst, & Banerji, 1974; Wason & Johnson-Laird, 1972), not only was there no control group, but the transfer task was administered only once, following an intervention. As the purpose of our study was to assess whether our students were able to transfer their newly constructed knowledge and skills following the enactment of a DBS unit, not to identify the causes of this transfer, and since our transfer task was administered only once, our study did not include a formal control group. Our goal was not to demonstrate that a particular curriculum, or teaching method supports the construction of new knowledge and its transfer; it was to show that the *enactment* of a DBS unit led to the construction and transfer of new knowledge and skills. Our understanding of the term *enactment* is that it includes all the variables that come to play when a teacher and students come together in order to teach and learn.

The call for scientific literacy for all means that students must be able to use what they learned in schools in their extra-school lives. The purpose of this study is just that, namely, to show that our students were able to solve an unsupported transfer task in part because of the knowledge and skills that they constructed during a DBS unit *enactment*.

Content tests.

The purpose of administering identical SPS-style (Bransford & Schwartz, 1999) pre-instruction and post-instruction written tests was to assess the students' science knowledge in the domains dealt with in the unit before and after its enactment. Students' ability to successfully solve a real-world design problem is dependent not only on their 'designerly' skill but also on their ability to apply the scientific knowledge and representations that are relevant to the problem. These knowledge and representations cannot be used if they have not been constructed in the first place (Klahr & Carver, 1988; Lee, 1998; Littlefield et al., 1988). Therefore, the purpose of these tests was to assess whether the students had constructed some of the new scientific knowledge relevant to the transfer task.

These identical tests were developed according to a model elaborated by our group (Singer, Marx, Krajcik, & Chambers, 2000). They were composed of 15 multiple-choice items and 3 open-ended items comprised of 8 sub-items. The tests probed for different levels of comprehension using low, medium, and high cognitive demand items as defined by (Costa, 1985), that focused on the specific science content addressed in the unit (Krajcik et al., 2000). The multiple-choice questions were of low and medium cognitive demand; the open-ended questions were of medium and high cognitive demand. Examples of a few test items are presented in appendix A. The teachers used the post-instruction test in lieu of a final exam.

One point was given for each correct response to a multiple-choice item on the tests. Each open-ended sub-item was also worth one point, but less than that was given if the sub-item was not responded to fully. Thus, if a full response to an open-ended sub-item 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 .5 points, so the item could be scored either 0 points, .5 points, or 1 point. The maximum attainable score on this test was 23 points.

Transfer task.

After the post-test was administered, the students' 'designerly' skills and their ability to use and construct relevant new scientific knowledge were assessed through a transfer task, that of designing a kite that could fly one mile high. This problem was chosen for four reasons: (a) the correspondence between the scientific knowledge and 'designerly' skill required to successfully solve this problem and those dealt with by the unit; (b) the topic was hoped to be of interest to many students; (c) the problem was straightforward enough to be reasonably completed by the students in a number of days; and (d) the structure of the task fit the PFL perspective – it required new learning, it was unsequestered, and it lasted long enough for the students to construct new knowledge relevant to the task.

Throughout the task, it was emphasized that any method of gaining access to information that would support the students' solutions was acceptable. For example, the students were encouraged to go to hobby shops, search the web, speak with friends and relatives who were engineers or kite enthusiasts, or talk with each other. All that was required was that they acknowledge the sources of their information and the relevance of this information to their solutions. As much as possible, the goal was to make the environment in which this task was completed a real-world setting.

The students worked in the same self-selected groups of four in which they had worked during the unit's enactment. They were given three days in the school library and at home to solve this transfer task to the best of their abilities. As in the *How Do I Design a Structure for Extreme Environments?* unit, this task began by giving the students a design specification – see appendix B. Each student was required to submit a solution that was required to include technical and concept drawings, a 3D model, a justification of the solution, and a description of the steps they went through in developing their solutions.

Completion of this task, like the post-instruction test, was not voluntary; the students' submitted solutions were scored and given the same weight as their scores on the post-instruction test in determining their term grades.

The submitted transfer task solutions were analyzed and coded separately for all the submitted solutions. The evaluation was done according to criteria that were based on six different categories taken from the standards for Applied Learning recommended by the New Standards Project (NCEE, 1997). According to the New Standards, “Applied Learning is about the capabilities people need to be productive members of society, as individuals who apply the knowledge gained in school and elsewhere to analyze problems and propose solutions…” (p. 3) The evaluation criteria were that the student:

1. Identified all the factors and variables that need to be considered.
2. Gathered relevant information.
3. Developed a range of design options.
4. Selected one design option to pursue and justified this choice with reference to functional, aesthetic, scientific or other considerations.
5. Used appropriate conventions to represent the design.
6. Established criteria for judging the success of the design.

Not surprisingly, these categories resemble the steps of the DBS learning cycle (Figure 1). The only difference between the two is that the third step in the DBS learning cycle (develop personal ideas) was divided into two discrete steps by the New Standards Project – develop a range of solutions (step 3) and select and justify one design option (step 4).

In each design solution, 0-2 points were given for each category: 0 points for no response, 1 point for a partial response, and 2 points for a full response. A partial response to a category was considered any instance in which mention was made of an aspect relevant to that category. For the response to be considered full, it had to shed light on the relevance of this aspect to the solution. For instance, if a student gave a list of URLs from which she had gathered data, this was considered a partial response. If, however, she listed not only the URLs but also described what information was obtained from each source and how this information was relevant to the transfer task, this was considered a full response. As there were altogether 6 categories, this meant that every submitted solution received between 0 and 12 points.

Most of the reported transfer studies have analyzed their results by comparing means: either the means of subjects' scores on identical or highly similar tasks taken before and after an intervention or the means of scores in an experimental group with the means of scores obtained in a control group (De Corte, 2002; Gick & Holyoak, 1980; Hendrickson & Schroeder, 1941; Judd, 1908; Thorndike & Woodworth, 1901). As mentioned earlier, control groups have been used either to verify that improved scores were not due to test-repetition or to subject maturation, or to assess the influence of a particular variable on transfer performance. The approach we have taken is different. We look for correlations between the scores obtained on a transfer task and either those obtained on a pretest or posttest that assess the subjects' knowledge in the contexts in which it was constructed. If the knowledge constructed during instruction supported the solution of a transfer task, we should expect the knowledge of the subjects *after* the intervention to be more highly correlated with success on the transfer task than their knowledge *before* the intervention. Thus, we compare the transfer-pretest correlation coefficient with the transfer-posttest coefficient to see if the second coefficient is significantly greater than the first.

This method of assessing the existence of transfer has a number of advantages for educational settings: a) Time is always a crucial factor in every classroom. Real-world tasks, like the one presented in this study, cannot be completed in a single lesson. Many teachers will rightfully hesitate whether to allot the multiple hours required to do a transfer task twice – once before an intervention and once after it. The method we used to assess transfer requires that the transfer task be administered only once, while the content tests can be used by the teacher both for grading and for evaluating the students' previous knowledge on the topics to be learned; b) This method does not require the existence of a control group. In a sense the transfer-pretest correlation serves as a comparison to which the transfer-posttest correlation can be compared, since the pretest assesses the knowledge of students who have not participated in the intervention. Note however, that while this method can be used to provide evidence that transfer may have occurred, it cannot be used to determine the different factors that affect transfer performance – for such an evaluation a control group is needed.

Results

Pre- and Post-Instruction Tests

The pre- and post-instruction tests were scored for all 149 students who participated in the curriculum enactment, but only 102 of these students completed both tests. The difference is due to absences, and students moving to and from the school. A t-test was computed on the pre-test scores to determine whether the students who did not do the post-test were less skillful than those who did, thereby biasing the post-test mean as an estimate of the effect of the unit. The t-test, which compared the scores on the pre-test of those students who did the post-test with those who did not, showed that it was statistically unlikely that the groups differed (t = 1.23, df = 116, p = 0.22). The following analyses are based on the test results of these 102 students.

The distributions of the pre- and post-test total scores are presented in Figure 2. The distributions are relatively normally shaped with little skew.

Insert Figure 2

The pre-test mean was 7.9 (SD = 2.9) and the post-test mean was 13.9 (SD = 3.6). A paired t-test revealed a significant difference between them (t = 16.8, df = 101, p < 0.001). In order to determine the degree to which the results diverged from the null hypothesis (Thompson, 2002), an effect size using the post-test mean, the pre-test mean, and the pooled standard deviation was calculated, giving 1.8. These results demonstrate that the enactment of this DBS unit led to significant and noticeable gains in the students' scientific knowledge.

Transfer Task

Only the students from the four classes led by the first teacher participated in the transfer task; the second teacher was unable to allot the three class-hours needed for the completion of the transfer task. 66 of the first teacher's students completed all three assessments (pre-test, post-test, and transfer task). Some of the submitted solutions to the transfer task were clear copies of others – in several cases the wording students used was identical. Unless the teacher felt that it was clear who copied from whom, only those solutions that were unique were used in analyses. Due to this elimination of copied solutions, 49 of the 66 submitted solutions were used in the following analyses.

On the first day of the transfer task, the students seemed interested in the project, challenged, and ready to go. They spent time discussing and developing a group understanding of what was expected of them, how they planned to go about solving the transfer task, brainstorming ideas for different elements of the kite, arguing over their advantages and disadvantages, and dividing up tasks between the different group members. Very few groups made use of the school's library; almost all went directly to computers and conducted on-line searches. Many searched the web for the term "mile high kite" and were disappointed when they couldn't find any sites that gave information about high-flying kites. They then wandered between the URLs of numerous kite manufacturers and kiting clubs. When class ended, most groups dispersed without coordinating between them any take-home tasks.

On the second day, most of the students seemed lethargic, lacking energy and motivation. It seemed that most of them had done nothing at home connected with the project. Many spent most of their time reviewing what they had done the day before; others surfed the Web. Then the news spread that someone had found a URL dealing with "Mile High Kites." This site quickly became a Mecca: everyone visited it, and many groups adapted their designs to match a particular kite portrayed at the URL. They then spent their time copying the kite's vital statistics and deciding how they could best use this information. Unfortunately, most of the students didn't realize that "Mile High Kites" was the name of a kite manufacturer and that this manufacturer made no claim that their kites could fly one mile high.

Little systematic writing had been done on the first two days. The third day was mainly spent writing the results of the first two days' work. In several groups there was one lead student who prepared a written solution that the other group members then copied. A number of groups were nervous because they felt that their solutions weren't complete.

Only few of the submitted solutions documented the process of reaching the solution; most of the students described their solutions as ready-made products, ignoring how they were created. Only few, therefore, described how and why they chose their solution from among the options they considered. Almost all the solutions documented the sources of their information and included a drawing of a kite. Few gave scientifically sound reasons why their kite, unlike standard commercial kites, could fly one mile high. Most solutions considered methods of evaluating their kite's performance but only few of these methods were practical. The mean of the final scores to the transfer task was 4.8 with a standard deviation of 2.7.

Analysis and results of particular categories for transfer tasks.

Each evaluation category of the design solutions was analyzed in order to identify which aspects of the design process the students had considered and documented in their solutions. In category 1 – identify factors and variables that need to be considered – 24% of the students gave a full response, 37% gave partial responses, while the rest did not explicitly mention any relevant factors. This is one of the two categories which look at the students' ability to draw upon the science content dealt with by the curriculum (the other is category 4 – selecting a single option and justifying it) Thus it seems that while a third of the students did not transfer this knowledge, the others did so in varying degrees. In categories 2, 5, and 6 (gathering background information, using appropriate conventions to represent the design, and established criteria for judging the success of the design) the students' mean score was over 1, meaning that the majority of the students' written solutions had documented partially or fully these aspects of the design solution. In category 4 (selecting a single option and justifying it), 40% of the students gave a partial justification of their solution. Almost half of the students (48%) gave no justification at all. This may be understandable due to the fact that only 28% of the students considered a range of design options (category number 3). Table 1 summarizes these findings.

	Category 1 Factors	**Category 2** Gather Info	**Category 3** Options	**Category 4** Justification	**Category 5** Representations	**Category 6** Evaluation
Full Response	24	45	22	12	37	33
Partial Response	37	30	6	40	48	51
No Response	39	25	72	48	15	16

Table 1: Percent of Students Responding to Various Categories

Example solution.

The figure and excerpt below are a summary page and a drawing which were part of the solution to the transfer task that was submitted by a Latino student who belonged to a group with 2 other Latinos and one Arab-American. This student scored 9 and 17 on the pre- and posttests respectively, both which were less than one standard-deviation above the mean scores. Her response to the transfer task scored 6, which was the modal score, less than one standard-deviation above the mean.

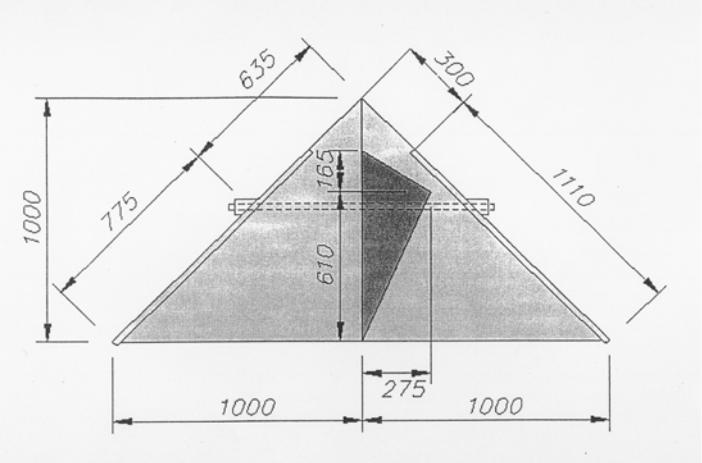

Figure 3: Drawing of Kite

The student's summary of the task is as follows:

First of all we wanted to find out why a standard kite could not fly one mile high, and its because of the higher wind speeds, and the higher the kite goes the heavier it gets so it needs a bigger wing span to get more lift.

We mostly got our information from the internet, the papers that were given to us and our teachers. We looked every where looking for this information, but we found it on the web sites provided on the back.

Enable to make a kite successful u need to know all the factors that need to be considered in designing the kite. Like what the kite needs to withstand, what it needs to fly or get of the ground, because you just cant lift it up. It's a 30-foot wide and 18 foot long kite. Then last but not least, what materials you can find to make the kite as light as possible, which we did.

We group didn't come up our own designs for the kite. We substituted what Richard Synergy did to build his kite to ours.

Our group has built a delta kite, which was the type of kite to break the world record. The drawing is about a scale of 1:50, it shows all the measurements of every side but on our drawing we have added pop flaps which are made so incase the kite manages to start diving and not fly, the pop flaps open up preventing the delta kite from reaching its height or goal. The materials that we are going to use to make the kite are; 76 feet of sporting hollow fiberglass spars 1.5 in diameter with a volume of .932 ft making it weigh 93.23 pounds total for the fiberglass, then to hold the kite a mile high we decided to use kevlar line because not only is it thin but it is a very strong material, its weight is .35 per 100 ft, and we needed 5800 ft to fly our kite. Making it weigh 20.3 pounds, we are also using nylon which weighs 62.9 pounds per cubic ft" and we needed 270 feet squared making the kite's nylon weigh 44 pounds but when we added on the pop flaps it weighs 44.6 pounds total. I know it doesn't seem that heavy but remember, you want the kite to be as light as possible. So now the weight the kite has to hold is a total of 157 pounds.

But that's not all we need for the kite. We need something to measure how high the kite is going, which we decide on using watches that use altimeters to tell how high an object goes by the air pressure, for example, the lower the air pressure is the higher your going and vise versa. Something like skydivers use.

Now to finish it of, we need a type of spool to roll up all 58000 feet of it. We found a motorized spool that will hold all this. This spool will help lift the kite as it reels it up and then letting the kevlar line go out as it lifts.

And that is our kite.

As a search engine we used yahoo to get some of these web sites like http://www.reropes.com/techdata/kev.dac.100.html and http://total.net/~kite/.

Analysis of her solution shows that:

a) She considered why a standard kite can't fly one mile high;

b) She considered the kite's shape, size, and mass and the wind speeds one mile high.

c) She did not consider the kite's tail (while she chose to work with a delta kite which does not require a tail for stability, she made no mention of this).

d) She did not consider the various components' structural integrity.

e) She gathered information from different sources but did not state what information had been gathered and for what it had been used.

f) She did not consider different options.

g) She made drawing of the kite but didn't build a 3D model.

h) She estimated (mistakenly) how long a line the kite would need.

i) In considering how she would test the kite she mentioned altimeters but not how they would be attached to the kite or how they would be read in-flight.

This analysis shows that this student was able to recognize the relevancy and draw on many of the science concepts dealt with in the curriculum (density and calculations using density, and aerodynamic forces and their dependency on size and shape). Thus, she transferred her knowledge of these concepts from the context in which it was constructed (a structure for extreme environments) to a new context (a kite that can fly one mile high). Her pretest shows that she was unfamiliar with these science concepts before participating in the enactment of the DBS curriculum.

She had also, except for developing a range of solutions, incorporated in varying degrees all of the ‘designerly’ problem-solving steps into the structure of her solution. However, as we have no evidence that she would not have done so even before the curriculum enactment, this cannot be taken as additional evidence of transfer.

Correlations between pre-/post-test scores and transfer task scores.

The central premise of this paper is that the scientific knowledge and ‘designerly’ skills constructed and developed during a DBS curriculum enactment foster the ability to solve a new science-related design problem. To evaluate this, two correlations were calculated: one between the transfer scores and the pre-test total scores, the second between the transfer scores and the post-test total scores. Only those scores of students who completed all three assessments – the pre-test, the post-test, and the transfer task in an honest manner – were considered, giving 49 cases. Scatterplots with trend lines and the Pearson correlation coefficients are presented in Figure 4.

Insert Figure 4

As the two scatterplots suggest, the scores on the transfer task have a stronger correlation with the post-test scores than with the pre-test scores; in fact, the square of the Pearson correlation coefficient of the transfer task scores with the post-test scores ($r^2 = 0.20$, $p = 0.001$) is fivefold as large as with the pre-test scores ($r^2 = 0.039$, $p = 0.17$). A null-hypothesis test for the difference between the two correlation coefficients (Cohen, Cohen, West, & Aiken, 2003) gives $z = 2.06$, which exceeds 1.96, the two-tailed $\alpha = .05$ significance criterion.

The knowledge of the students after the curriculum enactment is a better statistical predictor of their ability to solve the transfer task than their knowledge before the curriculum enactment; we believe this provides evidence that transfer occurred, that the scientific knowledge that was constructed between pre- and posttest supported the solution of the transfer task.

As a r^2 of .20 may seem small, it is important to note that there has been a preponderance of transfer studies that found no evidence of transfer at all (Detterman, 1993; Singley & Anderson, 1989)! Clearly, however, many other factors are at play here: the students' 'designerly' skills which, except for in two items, were not assessed in the content tests, the students' willingness to work for their grade, social factors, and others. We should not expect scientific content knowledge to necessarily be the dominant predictor of transfer performance.

Discussion

As this study shows, the enactment of a DBS unit created an effective environment for learning science. The students involved in this research showed significant increases in their science content knowledge (effect size of 1.8).

The research on transfer of problem-solving learned in science classrooms suggests that transfer of knowledge is not easily achieved (Bransford & Schwartz, 1999; Detterman, 1993). On the other hand, if the knowledge and skills constructed in high school science classrooms do not transfer to extra-classroom settings, these educational environments are not meeting the goal of helping students develop the capabilities necessary in our modern world (Lipman, 1991).

One method of assessing whether an educational program successfully supports such transfer is providing students with real-world problems, such as design problems or those suggested by the National Center on Education and the Economy (NCEE, 1997), having them attempt to solve the problems in real-world situations, and evaluating their performance. Because there is little experience with such assessment tasks, it is difficult to judge what levels of performance on them are desirable or acceptable.

Several studies have evaluated whether particular instructional strategies foster transfer (Gray, Camp, Holbrook, & Kolodner, 2001; Klahr & Carver, 1988; Schoenfeld, 1985). These studies focused on classroom tasks and were done by comparing means between two groups. An alternative approach to demonstrate that an educational program supports extra-classroom transfer is presented in this paper. This method looks for the presence of transfer by examining correlations between transfer task results and other measures of student knowledge in the context in which this knowledge was constructed. This study suggets that the scientific knowledge constructed during the enactment of a DBS unit transferred to the solution of a new design problem. The students' knowledge after the enactment of the DBS unit, as measured by a post-instruction test, predicted 20% of the variance in the results of a transfer task, while their knowledge before the unit was enacted, as measured by a pre-instruction test, was able to predict only 4% of the transfer task variance. Although this is not a large effect, we believe that this method of assessing whether a curricular enactment supports transfer to extra-curricular contexts and environments shows promise towards tracking transfer. Promoting transfer could be improved by repeating multiple units throughout an educational program. On each occasion, a new transfer task requiring new scientific knowledge but similar problem-solving skills would be administered. Besides examining the correlations described earlier, this approach would look for increasingly higher scores on consecutive transfer tasks while controlling for constant scientific knowledge as assessed by post-tests like that described in this paper. One could also design the transfer tasks such that the earliest tasks in the intervention support closer transfer and the subsequent tasks support further transfer.

This study is the first step in such a research agenda. In work underway we are repeating this study with larger sample sizes in order to obtain greater statistical power, we are assessing whether transfer is enhanced by consecutive enactments of different DBS units, which elements of the curriculum support transfer, what is the relation between students' attitudes and their achievements on transfer tasks, and the degree to which transfer is dependent on the quality of the classroom enactment of the curriculum. If it turns out, as we are hoping, that transfer performance improves following participation in consecutive enactments of various DBS units, this will be an indicator that transfer not only occurs, but it can be fostered and enhanced by a well-designed learning environment. Since finding indications of transfer have been uncommon, if we, by this approach, are able to show that transfer performance can be improved, such a result would imply that DBS and perhaps other inquiry-based pedagogies have the potential of fulfilling one of their central purposes – that of helping students develop science knowledge and real-world problem-solving skills that are necessary and can be used outside of the classroom.

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Appendix A – Sample Items from the Pre- and Post-Instruction Content Tests

2. 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.

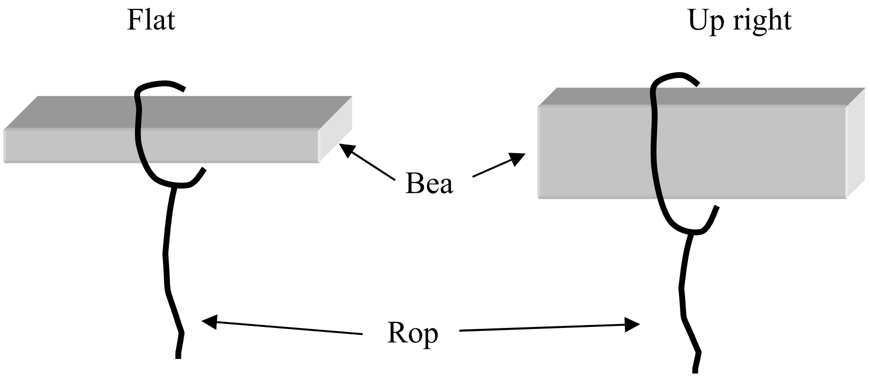
4. The floor plan of a house is drawn with a scale of 1:50. Using a ruler, an architect measures the dimensions of a rectangular room in the house and gets 12cm by 8cm. What is the actual area of the full-sized room?
   - A. 12 cm x 400 cm
   - B. 600 cm x 8 cm
   - C. 600 cm x 400 cm
   - D. 1.2 cm x 0.8 cm

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

	Mass (gm)	**Volume (cm^3)**
Block of Aluminum	725	268
Beaker of Water	1000	1000
Bar of Iron	1000	128
Cube of Ice	917	1000

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

16. 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: ____

____

19. An igloo 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.

Describe how you would test this structure to collect data on it ability to withstand static forces and dynamic forces, and how well it prevents heat loss.

(a) Static and dynamic force test description:

____

____

(b) Prevent heat loss test description:

____

____

Appendix B – Transfer Task Design Specification

Can You Design a Kite that Will Fly One Mile High?

The Mile High Kite

Design Project Specifications and Requirements

You have just spent several weeks learning what is involved in designing a structure for extreme environments. The purpose of this project is to see what you have learned by asking you to apply your new knowledge to a different but related problem. One way to find out what you've learned is to give you a written test; you've probably already answered it, hopefully very well. But tests aren't everything. You can get a perfect grade on an exam but still not understand it well enough in order to be able to use the stuff you learned in a real-world situation. That's what this project is for—we want to see if you can use your new knowledge to solve a real-world problem.

Your goal is to design a kite that can fly one mile high. You may wonder what a kite has in common with a structure for extreme environments. Actually, they have quite a bit in common. What keeps a kite in the sky? Forces. What makes a house fall down? Forces. What prevents a kite from flying? -- Its weight. What was one of the requirements from you structure for extreme environments? That it be light enough so that a couple of scientists could carry it out to the research site in a pick-up truck. How do you decrease a structure's weight? By using proper building materials and designing the structure so that it is strong, even though its light. The same ideas apply to a kite.

Although you may not realize it, you learned other things than just these scientific/engineering concepts. You learned how to go about designing a new product. You learned what's important to consider when designing a house, such as weather conditions, aesthetic considerations, materials, different structural elements, etc. You learned how and where to gather information. You learned about testing your design. And so on.

In this design project, we will be mainly interested in seeing how much you learned of the design process. Therefore it is of utmost importance that you document *how* you went about designing the kite. Just as there is no one best kite, there is no one right answer to this design project. People can come up with completely different designs and still get a good grade. However, even if you come up with a great design, if you do not justify your solution and if you do not document the process of how you reached this solution, you will get a poor grade.

And now, before you begin, here is the kite's specification, that is, the requirements it must fill:

KITE SPECIFICATION

1. It must be able to stay for at least 10 minutes at the height of one mile.
2. Preferably, but not necessarily, it should be made of materials that are available at hardware and hobby shops.
3. It must collapsible for easy transportation.
4. Special equipment, if needed, can be used in flying the kite.