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Engineering Competitions in the Middle School Classroom: Key Elements in Developing Effective Design Challenges

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Engineering challenges that involve both the design and building of devices that satisfy constraints are increasingly employed in precollege science courses. We have experimented with exercises that are distinguished from those employed with elite students by reducing competition and increasing cooperation through the use of tests against nature, large dynamic ranges in performance, initial prototype designs, and alternative methods of recording and presenting results. We find that formulating easily understood goals helps engage students in fascinatingly creative processes that expose the need for a scientific methodology. Such challenges engage male and female students equally, helping to erase the gender disparity in familiarity with the technology and skills common to physical science.

DESIGN CHALLENGES

Over the last 4 years, our team of teachers, developers, and graduate students at the Harvard–Smithsonian Center for Astrophysics, with National Science Foundation

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funding, has experimented with conducting engineering projects in nine local and six national schools. Children in Grades 5 through 9 have been challenged to design and build working devices as a major component of their physical science or technology courses. We feel we have made progress in developing challenges that engage the knowledge, skills, and interests of middle school students.

These activities, positioned midway between free-play and structured laboratory experiments, offer a unique opportunity for students to acquire science process skills and learn physical science concepts. While inspired by design contests for elite students, we experimented with their redesign so that they more productively engage students and lower barriers to entry for those without prior experience in such activities.

Design Challenges in Education

Design contests evolved as a popular and highly publicized component of introductory engineering courses at top-flight engineering schools (David & Willenbrock, 1988).[1] These student projects help to propel "students into open-ended, science-based problem-solving situations" (Samuel, 1986, p. 218). Within the technology and science education literature, professors and teachers report high levels of student enthusiasm for these competitions. However, few studies critically examine the effect of participating in these challenges within the cognitive or affective domains. Contrary to the prevalent belief that winning devices require student application of scientific principles, competitors rarely utilize theoretical knowledge in their designs, preferring strategic innovations that often circumvent the contest goals (Miller, 1995). For example, in one-on-one contests, a student may win only because his device interferes with the operation of the competing device.

The popularity of college design contests has had an impact at lower levels. High school physics teachers, in particular, have experimented with engineering challenges in their classes and in national competitions.[2] Most of these efforts involve the time-constrained construction of a working device designed to solve some imagined problem. Most use a variety of construction materials and allow only a single competitive test after weeks of building. Other forms of design challenges engage students in problems for which no working model is ever constructed or tested, only the theoretical design is evaluated.

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[1]Including the University of Melbourne, Colorado School of Mines, and Massachusetts Institute of Technology.

[2]Among these are the Junior Engineering Technical Society, Duracell Scholarship Competition, Physics Olympiad, National Science Olympiad, MESA (Mathematics–Engineer–Science–Achievement) Day at Arizona State University, Middle- School First Design Competitions, and NASA's Space Shuttle Involvement Project.

Over the last decade, technology teachers have shifted from teaching job-specific skills (e.g., type case sorting, welding, automotive repair) to pursuing more abstract underlying technological or scientific concepts so that relevant skills and knowledge can be used in new contexts (Perkins & Salomon, 1988). Creating such generalizable curricula has been recognized as the most significant problem facing technology education (Wicklein, 1993). Design challenges provide opportunities to practice transferring new understandings to new situations. Design projects within these courses are usually complex affairs with long periods of time spent in construction. Multiple goals and scoring rubrics determine the degree to which student designs satisfy constraints. These challenges emphasize designing and communicating solutions to complex problems, but are rarely optimized to reveal the underlying scientific principles.

National curriculum efforts have sought to merge science and technology by using: mathematics to find patterns in data through graphs and calculations, topics relevant to the world of the student, and technologies placed in the context of their historical and cultural development as solutions to human problems.[3] Recently, researchers have utilized a variety of approaches to investigate the impact of such activities at the precollege level. Four examples are

1. *Schools of Thought* program at Vanderbilt. This curriculum is characterized by "sustained thinking about authentic problems" such as writing a feasibility study for a *Mission to Mars*.[4] Students build domain-specific knowledge though extensive research on the World Wide Web and through group reflection and assessment.
2. *Houses in the Desert*, a 10-day culminating design project in the KIE/WISE (Knowledge Integration Environment/Web-Based Integrated Science Environment) curriculum that has students apply learned concepts to a new situation.[5] Students collect evidence from the web and other sources, and complete worksheets that help them utilize the principles of heat flow.
3. *Kids Interactive Design Studio*, which allows students to construct their own video games and play them (Kafai, 1996).
4. *Learning By Design* (LBD), a collection of open-ended project units that aid middle school students in exploring science concepts.[6] Learners build working devices while taking time out for activities that teach physical science concepts. Ap-

[3]For example, the National Science Foundation funding of Man-Made World, the product of the Engineering Concepts Curriculum Project; Technology for Science at the Technical Education Research Center, Cambridge, MA; Society of Automotive Engineers' All Systems Go at the Education Development Center; and T/S/M at Virginia Tech.

[4]Available: http://peabody.vanderbilt.edu/ctrs/ltc/Research/schools_for_thought.html

[5]Available: http://kie.berkeley.edu/KIE/curriculum/summaryHITD.html

[6]Available: http://www.cc.gatech.edu/edutech/projects/projects.html

plication of these concepts helps improve student projects (Kolodner, Crismond, Gray, Holbrook, & Puntambekar, 1998).

The first two projects utilize scenarios that present a problem to be solved by collecting and organizing information. The students, with the aid of their teacher, determine the quality of the solution. Students do not actually build working devices or models as they draw on scientific principles and reasoning. In Kids Interactive Design Studio, 16 fourth-grade students were studied as they each designed and built functioning computer games. No overall measure of the quality of the resulting games or any assessment of the discovery of programming or science principles was made. LBD utilizes design challenges as a long-term “backbone” activity, which students revisit to improve, applying science principles learned from other activities. Our team has used design challenges in a different fashion. Our challenges are the primary activity that students undertake, discovering both science concepts and honing skills from iterative attempts to build better performing devices.

Why Engineering Challenges in Middle School?

We have attempted to build on prior efforts to increase process skills, build content knowledge, and expose children to the possibility of careers in science and technology through a range of related activities. In interviews with scientists, technicians, and engineers, many relate youthful, extracurricular experiences that involve tinkering and experimentation with technology (e.g., building a crystal radio, puttering with an engine, repairing a toaster, or planning and building a sports-related device; Woolnough, 1994). At the middle school level, girls and boys express almost equal interest in science, medicine, and engineering as future careers (Cummings & Taebel, 1980).[7] There is evidence that girls peak in their consideration of the occupations that they consider appropriate during middle school and that their views become more restrictive afterward.

As most young women pass through school, they come to believe that science and technology have little to do with their future and thus, take fewer science courses, opting out more quickly than male students (Warren, 1990). Surprisingly, a woman’s choice of a technological career too often begins when she is treated as though she cannot secure a role in any technological endeavor, despite her interest (McMillan, 1991). Female students begin to lag behind male students in physics, chemistry, and earth science achievement by eighth grade (Beaton et al., 1996), just as youngsters’ concrete experiences are becoming generalized into scientific concepts. Lack of exposure to design and use of manual skills may be an impediment for many students, especially girls, because these skills are typically experienced outside of school. Taking time to develop these skills within school can help

[7]Roughly 21% of this population.

to close the gap for those without such opportunities and makes science accessible for all students. For example, British high schools have attempted to remedy this problem by promoting design competitions (50,000 students participated in 1993) titled CREeativity in Science and Technology (CREST). One of the most intriguing results of these increasingly popular contests is that female students win over half of the awards at the beginner's level (Woolnough, 1994). These challenges are supported by industry, with engineers often visiting participating schools.

International comparison data have shown that U.S. students have a high degree of mastery at factual levels of scientific knowledge (International Association for the Evaluation of Educational Achievement, 1988). American students lag in higher level thinking in science, including the analysis and integration of experimental results. Although "hands-on" activities are touted as a way to improve these abilities, the power of these experiences is severely limited when used only to reinforce known facts and concepts. When the teacher knows the result of every activity and experiment beforehand, the prime motivating force for the student to exercise originality and explore many options in completing the activity is absent (Cohen & Harper, 1991).

We view design projects as helping to show the connections between science concepts and solutions to real world problems. Making the right connections should result in better solutions. Applying the wrong ideas in a design does not just result in a lower grade; it means that a device will work less well than employing more applicable ideas—you cannot just talk your way around it. Failure stares you in the face. Testing is essential to finding which ideas apply, because the real world does not always conform to the idealizations we use and teach in science (West, Flowers, & Gilmore, 1990). For engineering and science, the world is the final arbiter, not the teacher or any other authority. Design projects also help students to develop manual skills; not all students will go on to college, and even those who do will have to cope with items that may not work well for their designed purpose. Engineering projects not only help students learn to be good at building things, but what the building of things entails. Technical careerists and consumers alike benefit from understanding that every product has been designed, tested, and manufactured by someone.

Relevant Research

All learners come to the science topics they study with preconceptions. The process of learning science means, for most, discovering weaknesses in what we believe and reconstructing our ideas or taking on a new set of beliefs that are more fruitful (Posner, Strike, Hewson, & Gertzog, 1982). Engaging students in experiences that challenge their ideas is critical in the process of change (Driver, 1973). These cognitive shifts from one conceptual framework to another can be compared to the "paradigm shifts" seen throughout the history of science (Kuhn, 1970). Design challenges allow students to test their preconceptions, permitting students to identify which ideas work better than others do. Especially useful are challenges that promote multiple solutions to a problem. Each can be evaluated by how well it satisfies constraints.

There are several aspects of the design process that are relevant to teaching science (Roth, 1998):

1. Design problems bring to the science classroom aspects of compelling real world applications.
2. Design is a form of cognitive modeling that crystallizes a conceptual model into a physical embodiment, either on paper or as a physical entity.
3. Design, especially iterative design, demands change. Alternatives are generated and assessed. Reflection on a particular embodiment and its performance is necessary to create the next iteration (Schön, 1983).
4. Design requires the combination of many kinds of knowledge, including facts, concepts, and skills—often exposing knowledge that resists formalization.

Among middle schoolers, a wide developmental range can often be observed in the same classroom. Skill Theory is useful in parsing cognitive development into four tiers of increasing complexity: reflex, sensorimotor actions, representations, and abstractions (Fischer & Lamborn, 1989). Adolescents can operate at all four of these levels, from dropping a “hot” electromagnet, trying to wrap coils as “neatly” as possible, to drawing their different designs on a storyboard, and on to describing and conducting a controlled experiment to provide convincing proof of their ideas. The distinction between working at a lower level without support versus working at a higher level with support marks the boundaries of a student’s “developmental range” (Fischer, Bullock, Rotenberg, & Raga, 1993). Our view is that by effectively scaffolding and supporting students at each of these levels, we will see substantial gains in conceptual understanding and in process skills.

TRIALS IN MIDDLE SCHOOLS

Our engineering challenges were developed by our team in summer institutes and further refined by project staff and teachers during the school year. Activities were tested in schools by 12 teachers nationwide. Our trials centered on six modules with three challenges in each. Students begin their challenge by listening to a scenario posed as a compelling problem. They then form into teams and copy an initial prototype design, one that was carefully developed so that anyone can quickly produce a barely functioning device. Students are then encouraged to revise and improve this design. Variables that may affect performance are brainstormed and listed during a class discussion. Students are free to choose which variables to investigate. In some classes a more structured approach is organized by students who divide up the work. Construction and testing lasts for about 5 to 10 class periods, with group discussions facilitated by the teacher.

One example is our two-dimensional suspension bridge challenge, where students start with a single sheet of notebook paper hung on two posts and supporting a 1-kg mass from an additional hole at its bottom edge (see Figure 1). In our test classrooms, students are immediately engaged by the problem, initially fascinated that a sheet of paper can hold up such a large weight. Furthermore, the challenge of reducing the weight of the paper seems almost magical. All students appear to be able to copy this initial prototype and delight in verifying its strength. They all begin at this same point, recording their findings for later reference. Many students start out individually mastering this first step and form into groups of two to four to work with their friends.

The next step is to improve the model bridge by cutting away some paper that the team views as extraneous. Much discussion ensues about where to make the cuts. Some students actively promote that the "feel" of the paper under tension reveals the critical, needed areas. Others generalize from bridges they have seen, arguing for triangles or graceful arches. Still others argue against structure and for a more "egalitarian" approach, that the paper should be lightened everywhere, attacking the bridge with a hole punch to fashion a "Swiss cheese" design. Students must record by drawing their design and adding a written description. The design is weighed first and students predict whether it will succeed or fail to support the 1-kg weight. It is then tested by the team, in full public view. Figure 1 shows the results of two student teams.

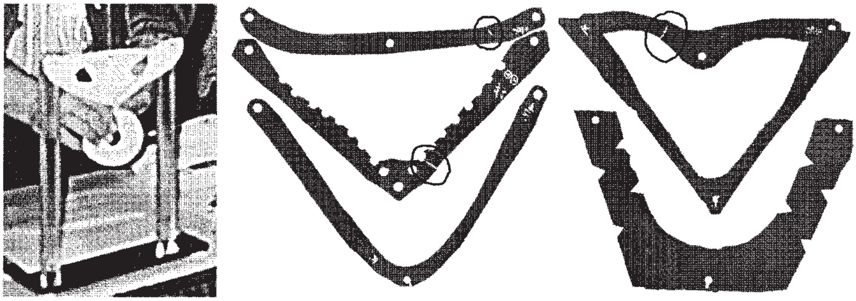

FIGURE 1 Designs for the bridge truss. The truss is suspended from the two holes at the very top, modeling a suspension bridge. The test load of 1 kg is suspended from the hole on the bottom. The top truss in the center set weighed 0.32 g and failed. The one immediately beneath weighed 0.45 g and failed. The bottom truss weighed 0.39 g and succeeded in supporting its load. Another team started with the shape at the top right, which failed; its second try was much heavier and succeeded. (The shapes have been printed in negative so that the failure tears can more easily be seen.)

Students quickly become aware of the variety of strategies used in approaching design challenges and find it useful to be aware of each other's ideas. Some are conservative, others are more risky. In Figure 2, the progress of four teams is shown (selected from a classroom of 14 teams). Some teams appear fearful of failure and make very slow progress (S & D), nibbling away at the shape of the paper truss. C & K took a more aggressive direction, removing more of the paper's mass at each step. For teams Phoagli and B & B, their first attempt at improving on the prototype design failed; it did not support the 1-kg load. In the case of B & B they tried one more time but were discouraged by their lack of success, whereas Phoagli backed off and retreated to a more conservative design, ultimately reducing their bridge to 0.2 g from a start of 4.3 g.

For this particular bridge challenge, most student trials were successful (41 out of 53), with the average truss weight declining for each successive trial in the challenge (see Figure 3). The log scale shows a roughly linear curve, representing an exponential decline in truss weight. Unsuccessful designs (12 out of 53) follow a

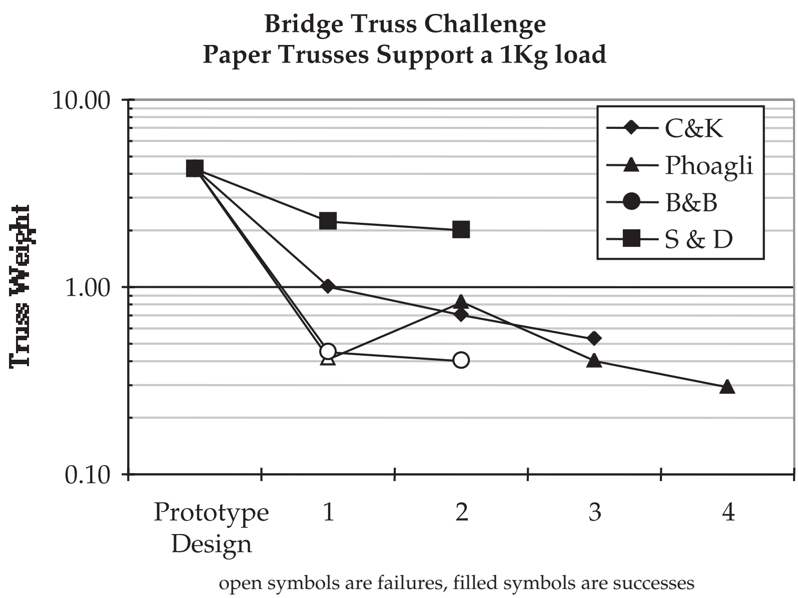

FIGURE 2 Four student strategies in solving design problems. Symbol labels are student-chosen team names. S & D pursued a very conservative strategy, working slowly and avoiding risky conceptual leaps. C & K was more aggressive. Both B & B and Phoagli immediately began with a highly risky approach, removing 90% of the existing material, both of which failed. However, B & B did not retreat from this failure and had another one. Phoagli decided to use a more conservative approach and ultimately improved their designs considerably.

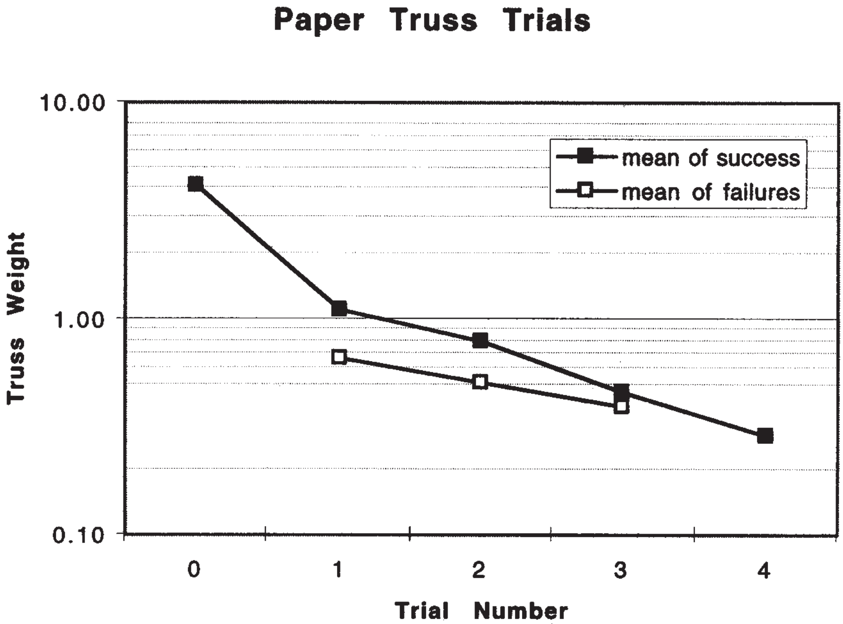

FIGURE 3 Results of paper truss trials. This graph displays the mean weight of successful and unsuccessful designs as a function of trial number. The weight of failed designs averaged out to be lighter than successful designs at each stage. Means are based on trials with 14 teams of students.

similar pattern. As expected, the average unsuccessful design for each trial weighs less than the average successful design. Designs fail because students have not yet learned which shapes work best. As they learn, in later trials failure weights decline as well. Students seemed quite content to continue their modifications until the third and fourth trial, perhaps until failure weights were roughly equal to success weight.

All student teams find some success in lowering the weight from the prototype design. The class period often starts with a discussion of discoveries from the day before, mitigated by those willing to share their failures or successes. Students make claims that they were first to discover some particularly effective strategy, which are argued out if there is a priority dispute. Teams often abandon or revise a work-in-progress if a similar design has been tested recently, whereas others may repeat an identical design if they feel the testing was done improperly.

Ultimately, the most effective designs begin to converge as the critical scientific principles are discovered. Students quickly realize that the suspension point and load-bearing points break if modified and learn that these are high-stress areas. Tiny nicks and sharp corners are often sites where tearing begins; smooth curves begin to replace jagged angles. Students begin to pay attention to portions of their design that are under the greatest stress; testing becomes more tactile as students feel for “floppy” or “tight” sections. Ultimately, the forces applied by the load are carried up to the supports by long smooth strands of paper, forming the elements of a rudimentary truss.

ASSESSMENT RESULTS

We have monitored students’ learning using a variety of tools. Open-ended pre- and posttests of students have measured changes in students’ ability to identify and generate hypotheses and variables, create and troubleshoot experiments, and interpret data presented graphically (Leiberman, 1997). Student interviews concentrated on tracking students’ explanations for the results they experienced within a particular design challenge. Classroom observations and storyboard analysis helped to reveal the role of the prototype design in organizing student work. Separate subject matter tests have been created that present choices between common preconceptions and a scientific view.

Science process skills have been measured using an 11-item, open-ended instrument developed by our project evaluator, Marcus Leiberman. Students read about a variety of experimental scenarios and identify testable predictions, as well as which variables can be changed, and which are controlled. They judge the quality of experimental designs. Students are also asked to design an experiment to find the effects of one variable on an outcome (e.g., “Your experiment is to find out if the kind of material that an ice cube is wrapped in makes a difference in how long it takes to melt”). Students are asked to identify the kinds of materials and equipment they would need, what tactics they might try to keep the same, why they would want to hold something constant, and how they might measure the outcome. A scoring rubric was developed to assign numerical values to each item response that gauges the number of correct predictions or answers, and the quality of original experimental designs. Item scores are based on a required maximum score or, for questions with unlimited response, the maximum is set at two standard deviations above the posttest mean.

The instrument was administered twice during the school year to our treatment group of 457 students in 22 classes (of 12 teachers). The results are promising (see Figure 4). Gains were significant (at the p = 05 level) in 8 of the 11 items, and the total score. Mean pretest score was .437 and mean posttest score rose to .553. The measured gain of .116 represents an effect size of .363 standard deviations. This year, we are planning to match physical science classrooms in our teachers’ schools to act as controls. We also plan to validate our test by giving it to science teachers and scientists alike.

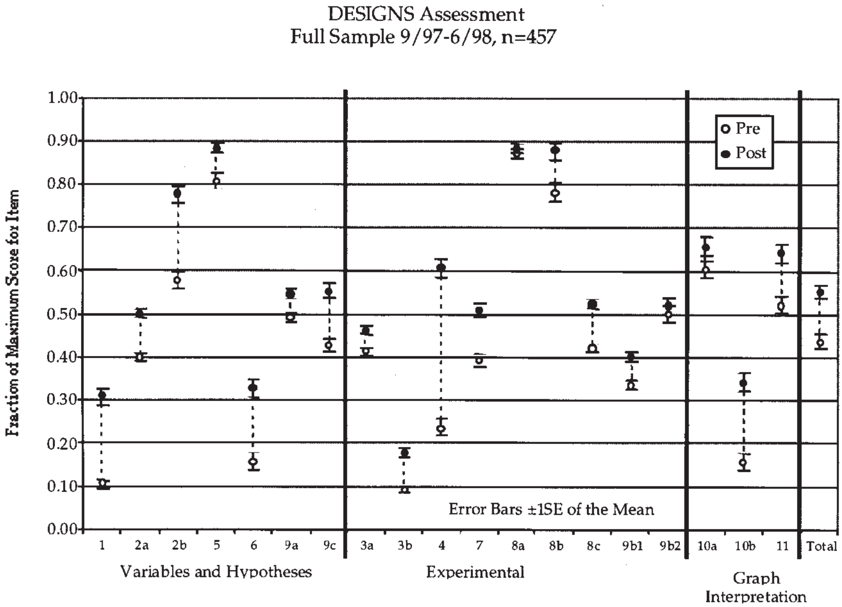

FIGURE 4 Results from science process test. Students took a pretest at the start of the year and an identical posttest at the end, which measured understanding of variables and hypotheses, experimental design, and graph interpretation. Gains were seen for each of the test items.

The bridge challenge described earlier is one of six. The others include optimization of a simple electrochemical battery for output, building an electromagnet with the maximum lift, a cardboard house that stays coolest under a heat lamp, a fan-powered windmill that lifts the most weight, and a vehicle powered by a falling weight. For each of the six modules, we are developing a separate test of science concepts based on the research literature on children's conceptions. At this time several versions of each test exist, with usually only a single classroom having taken a pre- and posttest for each version. An example is an electromagnet test that measures a student's ability to predict the effect of changing a single variable on the performance of a prototype electromagnet (see Figure 5).

This test was given both at the start and the end of a 5-day electromagnet module to each of 17 students who worked in groups of two and three. Students were shown a simple prototype design and asked to improve its performance in lifting as long a length of chain as possible. They could use more wire or nails and/or change the geometry of the electromagnet. Gains were recorded for 11 of the 12 items, with 3 significant at the $p = .05$ level. Large gains were found on three items where students held these initial misconceptions (see Figure 6):

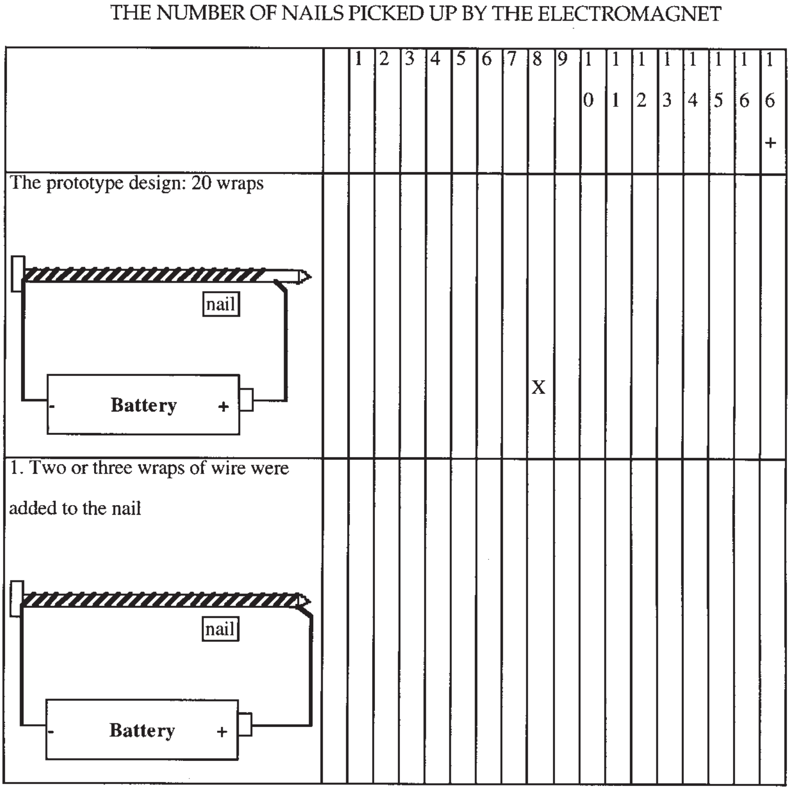

FIGURE 5 Item from the electromagnet test. Used as both a pre- and posttest, this example is a single item from a 12-item multiple-choice test, which asks students to predict the effect of a variety of changes to a simple electromagnet. Both visual and written descriptions are presented for each item. In this challenge students attempt to maximize the lift of an electromagnet by varying the layering, coverage, and position of its coils.

1. Only one lead was needed to make the electromagnet function (Item 4).
2. Electricity could flow through the wire's insulation (Item 3).
3. More metal in the core would produce more lifting force (Items 11 and 12).

Mean scores rose from .556 to .689, statistically significant at the .05 level. In units of standard deviation of the pretest mean, the effect size was .833 SD.

We also carried out in-depth interviews with a sample of students in several classrooms to track their progress and to gauge their movement from one developmental level to another. Sixth grade students working with electromagnets were all able to engage at the sensorimotor skill level. At the next, representational, level we found that students begin with single representations of electro-

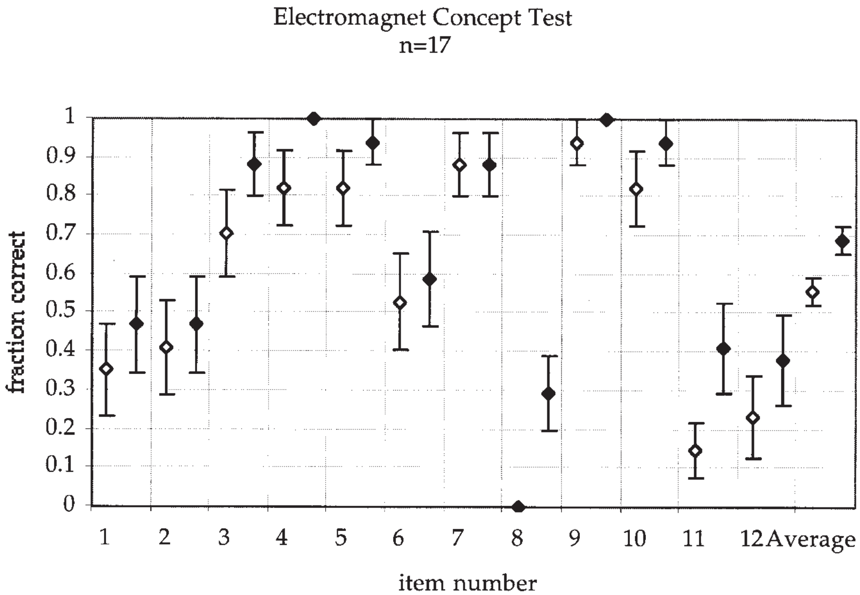

FIGURE 6 Electromagnet test. Seventeen 6th-grade students were tested before and after a 5-day module building electromagnets. Gains were seen on most items. Error bars mark ±1 standard error. Scientific principles tested were number of coils (Items 1, 2), complete circuit (Items 3, 4, 9), role of core and coil (Items 5, 6), and makeup of the core (Items 7, 10, 11, 12).

magnets (e.g., drawing a nail). Drawing a wire, and illustrating its ability to conduct with its insulation removed, is an additional representation. As students discover how to represent several features of their electromagnet they achieve a more sophisticated coordination of representations. With the support of the teacher and the requirement of drawing their devices, students found ways to show

1. The core as both a nail and a magnet.
2. The interaction between the nail and the distribution of wrappings.
3. How more or fewer wrappings affect the strength of the magnet.
4. Ways to rationalize predictions with experimental outcomes.

Ultimately, the challenge of building a better electromagnet depends on managing several representations at once and their complex relations. Out of many representations grow the first abstractions about electromagnetism.

For example, Eve was impressed by the fact that the insulation had to be removed from the ends of the wire for the prototype electromagnet to function. The importance of using insulation to only reduce the risk of a shock was the only role for insulation that she had ever considered. This view helped her imagine what the electromagnet in a telephone would look like before she began building her own:

> Inside a telephone it (the electromagnet) is all covered and everything (by the plastic body of the phone). So they probably do it (use wire) without the insulation. Because then they wouldn't have to worry about anyone touching it.

After experimenting with an electromagnet and watching others test electromagnets with all their insulation sanded off (and failing to function as a result), Eve starts to revise her view of insulation and build a theory of how the electromagnet works involving the circular coils, their proximity to the steel core, and some sort of storage of magnetic strength in the core.

> I think … it probably … uhmm the electricity … the wire that wraps around the nail … sort of … uhmm, like … the wire is carrying the electricity and it is touching the nail as well and while it is circling really, really fast around the nail. The nail sort of builds up … like very strong, maybe some of that electricity goes into the nail.

This model of Eve's, employing several elements recorded in her storyboard, leads her to a critical experiment of covering the entire nail tightly with more wire, with all coils wrapped in the same direction, and with the insulation removed only from the wire's ends.

> When I tried putting the wire all the way around the nail, almost covering the entire nail, it {the electromagnet} was really powerful because like all that there was so much force going around that nail.

Eve found evidence that the wire insulation had the purpose of keeping the electric current flowing "around that nail." She found reason to abandon the idea that current was flowing into the nail. Keeping track of separate representations and using them together in a concerted way is difficult for students, but possible if they are supported in recording their findings and talking about their ideas.

ELEMENTS OF SUCCESSFUL DESIGN CHALLENGES IN MIDDLE SCHOOL

Highly competitive and complex challenges are problematic in middle school. Although some students thrive on competition, we found that many of the male students and an even larger fraction of the female students did not feel competent to compete, fearing any engagement in competitions that required them to build from scratch.[8] The culture of many classrooms, especially in Grades 5 and 6, is often noncompetitive, stressing more cooperative investigations or "co-opetition" (Brandenburger & Nalebuff, 1996). Moreover, most students have no familiarity with the design process itself and lack the manual skills that would allow them to build a working prototype initially. The style and design of learning activities must fit the abilities and demeanor of middle school students. The four major elements are discussed later and characterize central features of the DESIGNS challenges that appear to resonate with middle school learners.

Tests Against Nature

Clarity in defining the goals of our challenges is critical. Performance goals for designed devices must be easily recognized by students so that there is no ambiguity in feedback concerning the performance of their design. Students must be able to act on the basis of their tests, to tell if their theory was fruitful when embodied in a device (Powers, 1973; Schwartz, 1998). If a goal does not inspire actions that students can evaluate from their own perspective, then they easily go astray, either detaching from the experience or defining a goal that they do understand. When students have differing goals, some stay occupied, blindly carrying out a procedure that the teacher desires. For others, more disruptive goals may develop (Ford, 1994), breaking equipment, wasting materials, or attempting to get their classmates to disengage. Having a clear goal, universally understood and accepted, helps to galvanize the class and creates a synergy in the efforts of many teams.

Competition is exciting, but it always contains the seeds of failure. Contests have both winners and losers, with the losers always outnumbering the winners. The extrinsic motivation of competition provides a positive incentive only if a student stands a reasonable chance of success (Woolnough, 1994). We have experimented with varying forms of competition to find one that increases students' self-confidence and encourages involvement. Although many design competitions pit one device against another in elimination competitions, we found that middle schoolers, taken as a whole, prefer to concentrate on improvement relative to their own starting point; they are not needful of others for comparison.[9] Students are quite often satisfied with determining how well their new design works compared to its predecessor, with the test itself the sole arbiter.

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[8]"Everything I touch breaks" and "I've never built anything before" were common statements that revealed a lack of self-confidence and willingness to participate in the "scratch-built" challenges.

[9]A good example of this is the static test of bridge designs by loading (Elementary Science Study, 1968).

Such "tests against nature" are seen as intrinsically objective and fair by students and can be carried out without teacher oversight.[10] Maximum wind turbine power (in cm-grams/second; Figure 7), aluminum-air battery output (in milliamperes), and sorting speed (in seconds) are all such measures.

Such tests have several advantages that may not be obvious. They involve students in the technology of measurement. The proper use of a stopwatch, scale, or stroboscope must be mastered to ascertain performance. Students are more engaged in predicting outcomes and in repeating their own measurements with a reliable test. Prediction helps in learning to estimate the magnitude of design changes, understanding the difference between large and small effects. This experience can be especially helpful in interpreting the inevitable variance observed in repeated measurement. For a design change to be considered effective, its measured increase in performance must be discernible from random fluctuations and experimental error.

Testing against nature has the advantage that it can be done at any time. Students need not wait for the whole class to finish to test their ideas. This means the testing stations are in almost constant use, hence the team with the best performing design to date shifts rapidly. Most students have a chance to lead the pack at some point over the course of the project if so inclined. Innovations are seen to propagate rapidly as the result of public tests.

Issues of a "fair test" often come up during a challenge. The teacher demonstrates the initial testing procedure. After students show proficiency, they conduct their own tests under the watchful eye of other teams. However, difficulties arise when trying to ensure that the exact conditions are replicated for each test. For example, while studying a sorting challenge, students must identify which card is missing from a full deck of cards, timing how long it takes to succeed. Eager to best their previous times, students inevitably blurt out a guess before their sort is completed. If they are correct, there is no problem, but they are usually premature and wrong. Do they get another chance? Do they have to start over? Students argue both sides of the issue to determine what is a fair measure of success and usually settle on the most conservative solution—one that can be carried out with the least possibility of subjective judgment. In this case, a single guess at the missing card ends the test; the student must be sure which card is missing to establish how well their sorting algorithm worked. As devices evolve, students recognize that testing can be biased when not well-controlled (e.g., squeezing the aluminum-air batteries while testing increases their current output). Squeezing the battery by hand during testing (which increases current output) was deemed unacceptable, as students felt it was subject to great variation by students of differing strengths. They did decide that squeezing by rubber

[10]For example, the speed of cars can be measured individually with a stopwatch over a distance instead of using a race against another car.

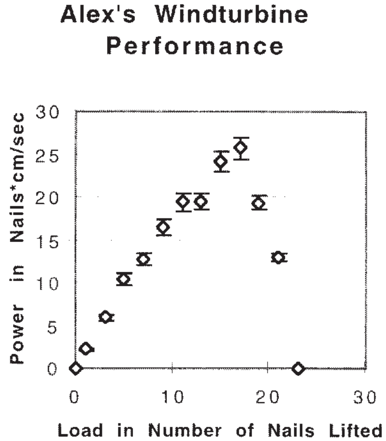

FIGURE 7 Wind turbine challenge. Students test their turbine designs making measurement in an airflow. Their measurements are independent of teacher assessment. Here they measure the time it takes to lift weights over a standard distance and graph their results. Note that the roughly parabolic shape shows features of stall load and free rotation. Bars enclose ±1-sec error in time measurement and ±1 cm in distance measurement.

bands or paper clips was permitted. The ultimate resolution of this issue was that the test procedure should be defined well enough so that anyone performing it would produce the same outcome.

Large Dynamic Range

Students look for verification of their ideas in the results of their experiments. Even small positive changes are seen as “proof” of their assumptions. This effect is particularly problematic when the changes are small, well within the range of experimental error. Establishing a classroom culture where acceptable evidence for claims must be large compared to experimental error requires challenges that exhibit a large dynamic range in measured performance. This setting helps students sort out which of their conceptions are valid and which are not. For example, cutting windows in the walls of model solar shelter (i.e., sitting under a heat lamp) lowers internal temperature by convection. By comparison, changing the pitch of the shelter’s roof makes little difference. Classroom discussion is intense around why some features produce big changes and others promote none at all. Those features that produce small changes are eventually attributed to noise and, along with ideas that decrease performance, are revised or discarded. A large dynamic range in test results helps students sort through their ideas and readily identify their misconceptions.

The requirement discussed earlier, that design challenges involve tests against nature, restricts the universe of design challenges that can be attempted. Because students do the testing, and lots of it, the measurement of performance becomes a major component in creating these challenges. Measurement techniques must be easily learned and mastered. Measurements must be repeatable and reliable. It helps tremendously when there is a large dynamic range in the performance variable measured. In one challenge two outcomes were measured: strength and efficiency. The strength of electromagnets progressed from 17 to 95 links lifted, an increase of 450% in 3 hr of building. In the same period, efficiency of the electromagnets (lift per unit cost) was also measured. Efficiency increased by only 55% over the test period and the maximum value was reached in the 1st hour. Performance measures that are simple quantities are easier for students to master. They can move to calculating ratios only after becoming familiar with the underlying measurements (such as efficiency). For example, wind turbine performance proceeds through optimizing lift (measured in nails), then to speed (measured in cm/sec). When these two measures are mastered, the third challenge employs both to optimize power output (measured in nails*cm/sec) with a fair amount of success.

We have taken care to identify measurement criteria that have large dynamic ranges (typically 10× to 100× in performance) while revealing certain key physical science concepts (see Table 1). For example, in building model shelters that stay cool under sunlight (or heat lamps), we have chosen to measure the difference between temperatures within the house and in the surrounding room and not simply the internal temperature, the thermal mass, or by reversing the challenge, the maximum internal temperature (Figure 8). This gives students a huge dynamic range to work with, because inexpensive indoor and outdoor thermometers measure ± 0.1 °F (or °C). From a ΔT of 50.0 °F for an initial design to one of 0.1 °F, there is a factor of 500× improvement. This was not the case for other temperature measurements we considered. Every challenge must be carefully crafted so that a clear goal reveals important underlying scientific principles while optimizing a single performance measure.

Students have theories about how the world works based on their own experiences. These “naive theories” can impede the mastery of new material. We have found that “common sense” notions, such as the streamlining of cars being an important factor even at low speeds, are deeply ingrained, even for the most capable students. Unless students subject these naive theories to tests, they will continue to have difficulty mastering scientific models that contradict common sense. We have chosen challenges so that when students make modifications to their projects’ designs, they are in effect predicting the outcomes of experiments before

TABLE 1

Challenges Involving Tests Against Nature With a Large Dynamic Range[a].

Topic	*Challenge*	*Variables Changed to Produce Best Performance*	*Prototype Design*	*Optimum Design*	*Dynamic Range*
Electromagnet	Maximize load lifted	No. nails, wire length, coil geometry, wire gauge, removing insulation, nail size	3 chain links	36 chain links	12×
Solar house	Minimum ΔT between internal and external	Materials, roof shape, ventilation, layered structure	50 °C	<0.1 °C	400×
Wind turbines	1. Max lift	Vane pitch, vane area, no. of vanes, arm length	3 nails	20 nails	7×
	2. Max speed		150 rpm	1200 rpm	8×
	3. Max power		1 nail-in./sec	12 nail-in./sec	12×
Electric battery	Maximum current, maximum voltage	Electrode area, collector length, electrolyte concentration, electrolyte, ratio of electrolyte to electrodes	10 ma	280 ma	28×
Bridges	Minimize truss weight	Truss geometry, depth of truss, rounded edges	4.8 g	0. 28g	17×
Gravity car	1. Maximum distance	Wheel diameter, load, mass distribution, axle diameter, starting angle	100 cm, 3 sec	8000 cm, 80 sec	8×
	2. Minimum speed				26×

[a]We currently use six sets of engineering challenges. Each has clear goals expressed as the optimization of some measurable variable. Students are free, within certain limitations, to modify their initial design in any way they wish to squeeze out the best performance.

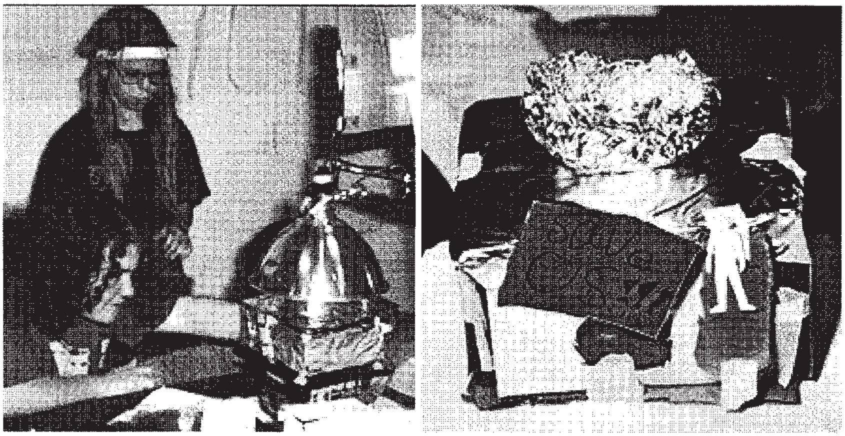

FIGURE 8 Students build a model solar shelter. A team of two develops and tests a shelter that keeps cool under a heat lamp. While designing and building several iterations, students discover how to minimize the heat gain though evaporative cooling, radiative reflection, insulation, and convection. The more pragmatic team utilizes methods discovered by others to build a winning design.

they do them. In this way students are confronted with their misconceptions. Uncovering inconsistencies in their own models opens students to the option of discarding their misconceptions and accepting more powerful concepts (Driver, Squires, Rushworth, & Wood-Robinson, 1994). Much as Karl Popper observed, as with scientists, students become aware experiments that “falsify” theories are as important as those that confirm their hypotheses (Miller, 1985).

Wind turbines (and other challenges) can be optimized in a variety of ways, creating instructive opportunities through successive challenges where the measurement criteria change but the materials do not. Maximizing lift, turbine speed, or power require the manipulation of different parameters to find improvement. Long, fat blades produce lots of torque at low speeds, whereas small, thin blades with a shallow pitch result in high speeds. Maximum power is achieved as a compromise between these two extremes. The same tradeoffs can be recognized in fans, propellers, and pinwheels, not to mention bulldozers, family cars, and race cars.

Although the primary measure in these contests has been performance, we have found advantages to recognizing student achievement in other ways after the competition phase is complete. Recognition has been given to students who make the most accurate predictions, who have the largest proportional gain in performance, or for aesthetic accomplishments. Design competitions can provide “winning” experiences for almost all students.

Iteration Beginning With a Prototype Design

Few middle school students have had the experiences with technology that help them believe they can design and build working devices, algorithms, and systems.[11] We have found that by initiating challenges with a step-by-step "cookbook" start-up design (such as an electromagnet with 20 wraps of #18 wire around an 8p nail), a much larger fraction of students become immediately absorbed in the activity. Diagrams and teacher demonstrations allow students with absolutely no background in construction to succeed in this initial but critical step. We have found that all students can reproduce a simple working model, albeit a poorly working one. Middle school students appear highly motivated to best what they perceive as their teacher's design, although the initial "prototype design" for each challenge is carefully crafted to be both easy to build and instructive to improve. This technique has proven especially helpful for students with few manual skills. For example, our two-dimensional "paper truss" challenge begins with a sheet of notebook paper suspended by two of its holes, easily supporting a 1-kg weight from a hole in its base. Students have no difficulty in constructing improved designs by incrementally cutting away paper in search of a lightweight truss. Students do vary in the degree of risk with which they are comfortable, some cautious, others rash. Both approaches have their value and liabilities, which do not escape student attention, just as in the design endeavor as practiced in society.

We find that students usually prefer to work on initial challenges individually to build their self-confidence, usually side-by-side with their friends. They quickly move to small groups, especially when allowed to help each other. This method replicates the way design is often carried out in the world of work. Engineering is usually practiced in teams, but teamwork only becomes productive after individuals develop skills and self-confidence (Hatfield, 1990). The fruits of increased self-confidence became apparent as students began working on their projects outside of class. Working devices became trophies that were demonstrated to friends at recess and lunch. Students then brought their optimized device home to show their families and friends, often receiving expressions of wonder and words of encouragement. Devices began to flood in from home (e.g., broken doorbells and small electric motors for the electromagnet module) for study.

We have found the use of a prototype design to be more effective than starting from scratch even when students are not building devices. For example, as an assessment activity, we compared students who were given the task of presenting evidence that their batteries improved as a result of their activities. Half of the students discussed the elements of a good graph and then tried to produce one that showed their findings. They were compared to another group that started with a

[11]It is a sad commentary that in a study of junior high students, many girls thought that they would probably harm machines by using them (McMillan, 1991).

poorly conceived “prototype graph” with three scattered points. Students beginning with the prototype graph were quick to identify its limitations. They began the task with confidence and stayed with it far longer than the group that began with the more conceptual approach. The prototype design group demanded less of the teacher’s time, discussed their work more with others, incorporated other groups’ data more often, and produced a more diverse set of representations of patterns. For many students, theory helps to organize their ideas only after they have had a sufficient number of concrete experiences.

We tested the impact of using an initial prototype with 10 dyads of sixth grade students designing and building electromagnets (Schwartz, 1998). Initially, the teacher demonstrated to students the assembly of a prototype design electromagnet. Lifting a single paper clip demonstrated that the electromagnet worked, but did not reveal how well. The instructor then posed the challenge: “Do you believe you could improve this design?” Students suggested strategies and the teacher noted those suggested changes on the board for future reference (e.g., number of nails, size of nail, number of wraps, etc.). This step established the potential variables students could investigate. Students were encouraged to only change one variable at a time.

The dyads were then split into two groups. One required to build and test the prototype before embarking on their own designs and the other group was free to start in any fashion they wished. Examining the work produced by the two different groups shows a difference in their ability to change one variable at a time with the prototype group succeeding in holding all variables but one constant for 80% of their attempts, while the nonprototype group succeeded only 53% of the time. A t test comparing the 10 dyads shows the differences as significant at the p £ .05 level.

Perceptual control theory (Powers, 1973) argues that the goal must be clear enough to learners that they can first envision ways to achieve the goal, and second be able to interpret the feedback that their actions generate. Those dyads starting with a prototype design are reinforced in their pursuit of identifying variables by having an unambiguous reference with which to compare their later designs. To the extent that teachers wish to model how scientists use controls in their experiments, the prototype design does scaffold this objective.

Using a prototype design rather than a pure discovery approach helps to support students in working at a functional level higher than that of which they might otherwise be capable (Fischer & Pipp, 1984). Venturing into a new level of abstraction, that of discovering the scientific principles governing a device’s performance, is aided by having students able to physically handle and examine concrete manifestations of their ideas. We like to have students build and save their designs whenever possible, so that the objects can be held, examined, talked about, and shared with others. Rather than having only data surviving from an experiment, preserving the concrete object helps students to concentrate on the abstraction of differing performance due to an underlying principle.

The opportunity to perform many iterations is very helpful for students. Because of the short iteration time, students can test many ideas thereby developing confidence and honing their building techniques. Also, we have seen no evidence of “dry-labbing” (falsification of test results) that students engage in when more conventional laboratory experiments do not perform as expected. A short time between iterations serves to reduce the “ego investment” by students in their designs. When a device does not perform as expected, they appear less likely to blame themselves and, in a more healthy and constructive fashion, blame the idea for not working. Design-and-build challenges at higher grade levels are typified by spending weeks on a design and testing them only once. We find a mixture of small success and failures keeps student engaged and productive.

Purposeful Record Keeping

Conveying one’s ideas and issues to others is critical in the modern workplace. We have found ways to facilitate communication by planning projects so that cooperation and communication are encouraged and rewarded. All tests of devices and processes in DESIGNS are public; others can watch and learn from what they observe. We have experimented with personal laboratory notebooks to record progress and ideas, finding that few students seem to see any intrinsic value in careful record keeping. Only when these records repeatedly became of use during reflective activities did we observe a gain in popularity and a serious increase in record-keeping activities.

A powerful reflective technique for students is the making of storyboards. The storyboard first originated in the Disney studios as a way to outline the evolution of a cartoon without committing to all the details necessary in the finished product (Denison, 1995). Student storyboards are used to document the story of how a challenge was met over time. It is not created at the beginning of the project. Neither is it created at the end of a project as a summary of what was accomplished. The storyboard is a series of frames created by students during the project, each frame displaying the latest solution to the challenge. Starting with the prototype design, students typically create three to five frames (of drawings and data) that tell the story of their investigation (Figure 9). These storyboards serve a quite different purpose than “lab reports” in that they document the sometimes curious routes to discovery and include predictions, interim results, insights, and failures. The storyboard provides a pictorial as well as a literal database of student progress in trying to meet the goal of improvement. Student devices are either attached to or drawn in each frame.

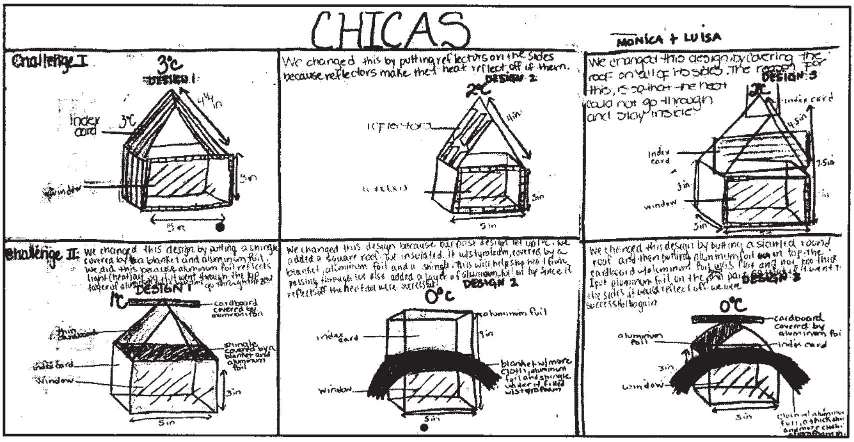

FIGURE 9 Solar shelter storyboard. Here a team of two keeps a record of their experiences during two challenges. For the top three cells the students progress by adding aluminum foil strips to reflect the lamp's rays, reducing the temperature by 1 °C from the prototype design. A subsequent sealing of the "attic" space is predicted to be useful, but does not lower the temperature of the house.

Holding variables constant is not a natural strategy for students (Schwartz, 1998). They perceive such an approach as too wasteful or slow, wanting instead to try many ideas simultaneously. It is only when the storyboard is reflected on, after a construction is complete, that a student can be directed to focus on defining exactly which change in design produced the claimed improvement. Students from other teams often exhibit healthy skepticism, pointing out alternative hypotheses for changes in performance. Those storyboards that show a single variable change ultimately receive the recognition for a discovery. Students learn how easy it is to fool themselves into believing that the wrong variable was responsible for a change. The richness and visual nature of the storyboard record helps students to draw new knowledge from the data they have collected.

Storyboards become respected evidence for claims of discovery. In some cases (such as electromagnets) the actual devices can be fastened to the storyboard, adding authenticity to the record. In other cases, the development of drawing skills, construction of flow charts, or graphing competence become well documented and a subject for student reflection. Teachers find storyboards a useful focus for reflective study, asking: How did student drawings change? Did they more clearly represent the device? Which test was most productive? Which change could the student have done without? If the student were to draw a fifth frame, what would be changed and why?

CONCLUSION

Engineering challenges are viable alternatives to free exploration activities and traditional laboratory experiments for middle school science students. Although originally utilized at higher academic levels, these challenges can be adapted to meet the abilities and interests of middle school students. We have found that special attention must be paid to student goals and student preconceptions in designing such challenges. Students must "buy into" the goal of the activity; they must understand what is expected of them or they will flounder. Moreover, they must be able to utilize the feedback that results from testing their ideas. The design challenge must throw into stark contrast the prior beliefs of the student and the science concepts that we wish them to learn. Through iteration and public tests these concepts are discovered and found productive. These design tasks can also motivate attention to accurate record keeping.

Through research in 20 classrooms we have been able to identify several attributes of design challenges that are effective with school children in Grades 5 through 9. Student designs should be tested and modified often; there should be at least one iteration by each team of students within each class period (45–55 min). These tests should not be made explicitly against each other's designs, but against nature, measuring with stopwatch, scale, ruler, or thermometer. Students should set their sights on learning to control nature, not on outperforming another team. Students delight in their own improvements relative to where they started, some progressing gradually, others in fits and starts. Teachers should expect and point out a variety of attitudes toward risk, and failure should be acknowledged as a failure of ideas, not of people. All tests should be conducted at public "test stations." Although this may cause a bottleneck upon occasion, students learn important lessons from observing the performance of others' designs, among them novel ideas that they may later choose to incorporate or neglect in their own designs, and issues of testing in a uniform and fair manner.

Design challenges should possess an intrinsically large dynamic range in performance of a single measure; there must be lots of room to improve. For students to find their prior conceptions lacking and be willing to adopt a new idea, the evidence must be overwhelming. We have aimed for a 10× improvement in performance as an attainable goal for students and continue to modify our challenges to increase this range. Our latest record involves building a loudspeaker from scratch. We are able to attain a gain from +1 db over ambient noise (60 db) to +50 db (110 db). This represents a 100,000× gain in efficiency (10^5).

Starting with an easy-to-build but poorly functioning "prototype design" appears to offer great advantages to students who have few prior experiences in designing and building. Constructing an initial functional "cookbook" design, no matter how poorly it performs, results in a feeling of accomplishment for students that helps to propel them toward investing in improvements. Utilizing comparisons to this common starting point also helps while discussing the improvements and failures that teams experience, and aids students by having concrete manifestations of abstract principles. Without the set procedure of most traditional laboratory experiences and the prior knowledge of expected results, we have seen little falsification of data or copying of other's results.

The need to utilize the data from many trials requires that students pay close attention to formative record keeping. Alternatives to traditional laboratory reports have arisen that preserve student ideas and the results of tests. The many iterations involved in each challenge have inspired journal-like storyboards that are constructed during, not after, the week-long design challenge.

Our design challenges contribute to a growth in science process skills and in students' realization of the unique aspects of the scientific process. Uncovering the causal links between changing parameters and the resulting performance demands that students discover how to vary one thing at a time. Trials proving that an idea that does not work can be more valuable than finding a change that does improve performance. Good record keeping is essential in settling disputes concerning who had which idea first. Replicability of results by more than one team adds credibility to claims. Paradigm shifts abound as major discoveries are made and sweep through the classroom.

Rather than preserve the initial advantage of those students with prior building experience, design challenges help students develop skills in planning, construction, and testing. Although many female students first appear at a disadvantage in these challenges, they soon learn the necessary skills. When competitions go on long enough, they often challenge the male students, showing how the playing field can be leveled through thoughtful changes in the middle school science curriculum.

ELEMENTS OF SUCCESSFUL DESIGN CHALLENGES IN MIDDLE SCHOOL

Clear goals: Challenges should reveal to students the exact nature of what is being asked of them. Challenges should invite students to chose (or to consider) strategies they feel appropriate to attain the goal.

Tests against nature: Designs should be evaluated using highly reliable tests against nature and not rely on complex rubrics or subjective judgments of teachers or students.

Prototype design: Students vary in their construction skills and level of confidence. Building an initial "cookbook" design, albeit a poor performer, is a necessary first step to engage students, develop rudimentary construction skills, and familiarize students with test procedures.

Multiple iterations: Students learn from their failures as well as successes. To encourage the testing of ideas, devices should be quick to build and modify so that many tests can be performed in a short period.

Large dynamic range: Whenever possible, device performance should increase dramatically over several days of building. A high signal-to-noise ratio is necessary for students to find experiments and their data convincing and to uncover the underlying science.

Employ purposeful record keeping: Student records should be formative, capturing all attempts and trials. They need to function as a resource for the resolution of claims of first ideas and for the focus of class discussions.

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