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Integrating Science into Design Technology Projects: Using a Standard Model in the Design Process

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Technology education at the elementary and middle school levels has been undergoing major revisions in recent years. There are currently a variety of pedagogical approaches to introduce elementary and middle school students to the processes and content of technological know-how and knowledge. These approaches span a range from a completely open-ended design challenge to a tightly structured, lengthy curriculum program. Given that there is an on-going debate about the nature of technology education and that current practices may be seen as transitional in nature, there are shortcomings in these practices that need to be addressed. One problem shared with other domains, such as science and mathematics, is a lack of depth. There is a need to balance the making of models or products with critical thinking. In addition, it is recognized that basic science knowledge would enrich and result in a more effective design process, at least in some areas of engineering technology. Given the time constraints of elementary and middle school teachers, this possible enrichment tends to be neglected. Coming at this from the other direction are science curriculum programs and teachers who recognize the highly motivating aspects of design problems. They tend to emphasize the inquiry process over the design process. What could be a mutually reinforcing and rich undertaking, where inquiry and design are dealt with in-depth, currently tends to be a situation where both are slighted. I will propose a pedagogical model that attempts to address this issue by advocating a special type of integration. This will be illustrated by a case study of a 4th grade class building and investigating a model windmill. I will illustrate how the introduction of what I call a “standard model” can be used to help students develop some basic scientific understanding, which can then be applied to making a more effective design. I will also discuss some issues of implementation that need to be addressed if such an approach is adopted.

Characterizing Different Approaches to Design Engineering

Before elaborating on this pedagogical model, I would like to place it in a broader context of research, practices, and current thinking regarding the integration of science, math, and technology. Most of these practices and curricula can be characterized into four basic categories through the examples that follow.

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1. Students are given a challenge having defined constraints and a set of materials. The teacher provides some guidance but the students are pretty much left up to their own abilities to carry through to a completed project. Here, both the design process and any potential science are implicit and undeveloped. A number of extra-curriculum programs seem to operate in this manner.
2. Design projects are presented to students in their science class. Teams of students assemble models with slight variations in their designs. Some experiments are conducted using the models, but these are not necessarily related to the improvement of the performance of the models or the overall design. The model is the means for introducing basic science concepts such as force and motion. The *Science Technology for Children (STC)* 4th-grade curriculum unit, "Motion and Design" is an example of this approach.
3. An integrated program of technology, science, and mathematics is organized around a "big idea" such as energy transformation. Concurrently, students might investigate the energy food value of trail mixes in math, measure heat energy in science, and experiment with photovoltaic cells in technology. This is part of a unit in the curriculum program *Integrated Mathematics, Science, and Technology* (1999). Similar kinds of juxtapositions happen in the *Biological Sciences Curriculum Study* (BSCS) middle school program. If there is design, it tends to be secondary to the teaching of science and technology concepts.
4. The fourth type of pedagogical model is a deliberate and explicit combination of design and inquiry. The overall context is a design project. Students are challenged to design and build a working model of a technological artifact, such as a flying toy, windmill, water wheel, or balloon-propelled car, with a limited set of materials and initial performance criteria. After preliminary models are designed and tested, there is a shift to a standard model, which is used to carry out inquiry providing for a more controlled context for introducing basic science concepts.

   Experimenting is a way to gain information about ways of improving the performance of the model as well as collecting data and evidence to support possible hypotheses about the functioning of the model. The hypotheses are connected with basic science concepts. After some experimenting, there is a return to the preliminary design models that are either modified based on the newly gained knowledge or completely redeveloped and tested. "The Flying Toy—Challenge 3" (SAE, 1999) of the curriculum program *World in Motion II* is one example of this approach.

It is this fourth example that I will develop in some detail. Taking this approach recognizes that design and inquiry are separable but closely intertwined. Each process needs to be given adequate and explicit development if students are to gain a sense of both. This would be in the spirit of the recently published *ITEA Standards* (2000) where it is stated that, "Design is regarded by many as the core problem-solving process of technological development. It is as fundamental to technology as inquiry is to science and reading is to language arts" (p. 90). The National Research Council and the American Association for the Advancement of Science also recognize the importance of design in technology by specifying a separate set of standards for technological design. As illustrated in the above examples, there are varying interpretations of how these standards get implemented, particularly in the context of science curriculum and practices in the classroom. I will propose that the first three approaches described above do not go deep enough in terms of design or inquiry.

Relevant Research for Integrating Engineering and Science

A limited number of studies have been conducted on the effectiveness of integration of science and technology. Childress (1996) reviewed some of this research and found results were inconclusive. His own study had equivocal results but suggested that there is a possible impact when the teaching of science concepts is introduced into a design project. Students involved in the *Technology, Science, Mathematics (TSM) Integration Project* (1995) worked with model windmills. The wind collector was hooked up to a generator. The challenge was to improve the performance of the collector as measured by electrical output. The experimental group was given one and one-half class periods each of special instruction in science and math. During a second iteration, the experimental group also received instruction related to the pitch angle of the collector blades. This is compared with the control group, which did not receive this extra instruction.

Childress concluded that "there was evidence that the students did, in fact, apply what they learned in the correlated instruction" (1996, p. 23). Through interview questions, students indicated that the specific demonstration with a Tinker Toy-type model seemed to impact their thinking. What was interesting and significant was the recommendation for future studies. Childress commented: "It is conceivable that the results of the pitch angle experiment were not transferable to the types of solutions that the students were working on; similar studies should use the actual student-made solution as teaching aids and demonstration props."

Here he is referring to the practice of using the Tinker Toy model for the demonstration while the students used other materials for their own constructions. He is recommending that the science experimentation be done with the students' own models. From my experience, the amount of exposure to the science part may not have given students enough time to fully assimilate the significance of its implications for their project. Both of these practices are incorporated into the example I will develop below which also involved working with model windmills.

Other research that is related to the issue of integration has studied how students approach problems in the school context. These studies suggest that elementary-level students, and to some degree middle school-level students, have a natural tendency to take school projects and turn them into challenges. Given a flying toy, students will naturally work to make it go farther or faster, or a model windmill, to lift more and more weights.

Schauble, Klopfer, and Raghavan characterized features of students' engineering and science models of experimentation in their 1991 study. They describe an "engineering approach" as one where there is comparison of highly contrastive instances where students search for variables that they believe are causal. The "science approach" is characterized as one where there is establishment of each important variable and a systematic testing of these variables. Students were given tasks that promoted these two different approaches. Significantly, the group that started off with an engineering task and then moved on to a science problem generated more inferences about variables. The authors speculated that the engineering task provides an easier entry point and a more focused goal for the students. During their work with students, Shauble, Klopfer, and Raghavan repeatedly asked them questions, attempting to get them to reflect on their learning. "Unless they receive practice and support in developing appropriate models of scientific inquiry, children's experimentation is characterized by narrow search, overemphasis on variables presumed causal, and difficulties in interpreting simple patterns of data showing covariation or lack of co-variation between candidate causes and events"(p. 879). These comments suggest that there has to be a deliberate and explicit move on the part of the teacher to take time in a design challenge to help students sort out relevant variables and conduct controlled experiments. This will be partly illustrated in the windmill case study I will present later.

The need for making thinking explicit is also called for when helping students gain a deeper sense of the design process. Kimbell, Saxton, Miller, Liddament, Stables, and Green (1997) generated a list of operational strategies, which they present as essential for students to go beyond functional skills to higher order thinking. Some of these strategies include iterative thinking, optimizing values, managing tasks over time, and collaboration. They claim that helping students become explicitly aware of these strategies will promote transferability across a variety of tasks. These strategies are dealt with in a more detailed manner by Kimbell, Stables, and Green (1996) in their outline of key stages in children's development of design capabilities. They isolate "facets of performance," which they consider central to the development of these capabilities. These are investigating, planning, modeling and making, raising and tackling design issues, evaluating, extending knowledge and skills, and communicating. As these are elaborated on in the case studies the authors present and the specific characteristics describing these processes, there is a mix of inquiry and design. For example, some of their descriptions of what constitutes investigation and extending knowledge and skills could be applied as well to describing processes of inquiry. Modeling and making are more clearly related to a design process but, as will be illustrated in the case study of model windmills, scale models are a context for dealing with both technological as well as scientific issues.

A curriculum program and teachers can present problems to students with specific goals but students have ways of reacting to these problems that may counteract these goals. For instance, Millar, Gott, Lubben, and Duggan (1993) investigated how children aged 9–14 interpreted an investigation in a school context. They observed that the students used several kinds of approaches (frames) in response to a posed problem. These were characterized in the following manner:

- Engagement frame: using the materials without any apparent plan or purpose
- Modeling frame: focusing on the physical appearance of the materials working to achieve an effect but not making any comparisons among characteristics
- Engineering frame: attempting to achieve an optimum effect
- Scientific frame: making comparisons, carrying out tests, and making conclusions about trends

Students initially started out working within one of these frames, but "over 75% of the changes of frames that occurred were towards an engineering frame" (Millar et al., 1993, p. 22). The authors' interpretation of these results has important implications. Children interpret a given task in a form in which they believe they can succeed. In other words, if a given task appears too demanding, it is reformulated, almost intuitively, as one which is feasible and manageable for that individual or group" (pp. 223–224).

These findings, as well as the experience of master teachers, suggest that students have to be brought to an explicit understanding of the need to carry out tests in a systematic way. This includes isolating variables, setting up controlled experiments, and making valid inferences based on evidence. Likewise, students need to reflect on the processes by which they arrive at a final prototype in order to develop an understanding of the design process. Younger students, it appears, need to be given explicit directions about ways to conduct controlled experiments and need to talk about how they are moving through a design problem. The challenge for the teacher then does not appear to be getting students to work at solving an interesting problem; rather, it is getting them to see the need to take time to conduct formal experiments and reflect on how the overall system appears to work. My impressions are that science teachers will attempt to do this often, but will neglect to also make explicit the design process and related concepts such as troubleshooting and optimization. Technology education teachers are supposed to emphasize and make explicit the elements of the design process. Why not try to find a way of bringing all of this together within the context of one project?

Integration of any set of knowledge domains needs also to be considered in the larger context of the *Third International Mathematics and Science Study* (TIMSS) results and their interpretation. As the most recent results show, U.S. middle school students fell behind those of other comparative countries even though they did relatively well as fourth graders. Part of the TIMSS project also involved a close look at the pedagogical practices of some of the participating countries. It became apparent that there are real differences in how the same subject matter is treated by teachers and the type of coverage given to this subject matter. By now the familiar phrase *depth versus breadth* has been a familiar cry of some educational leaders. What this means is also being debated, but there does seem to be a consensus that fewer topics should be explored and dealt with in greater depth. Projects that attempt integration are prone to cover a lot of content and process in a short amount of time. Any attempt at integration needs to address this issue.

Integrating Science into the Design Process

Based on work with technology topics, such as the Flying Toy Challenge (SAE, 1999), it has been found that a three-phase approach can be used that allows for a meaningful integration of science-type activities during the course of a design project. (Some current curriculum development efforts, such as TERC [formerly the Technology Education Research Consortium], seem to be proceeding along similar lines.) The first phase is an open exploration during which students are free to try out their own ideas attempting to build something that is functional but usually not very efficient. The second phase involves the adoption of what can be called a *standard model*. This is used to carry out systematic testing of essential variables of the system. The third phase is a return to the design process, using the newly gained knowledge to rebuild and make a more effective design. The key element of this approach is the use of a standard model. It is an essential ingredient, because it provides a knowledge base that can result in a more effective final design.

The First Phase-Open Exploration

The first phase should be a relatively open-ended exploration during which students are given wide latitude in trying out their own designs. This phase is similar to what Kimbell et al. (1997) described in their key stages of investigating (pp. 56–57). It is not a completely open situation, because they are constrained by the limited set of materials and specific performance criteria. During this time their mode of operation can be characterized as highly intuitive and based on tacit knowledge (Dorfman, Shames, & Kihlstrom, 1996). There are limited analyses of the overall challenge and any problems that occur. This means that if one observes students' behavior, it would seem they are deliberative in their constructions. But when pressed to make explicit their thinking, they have difficulty expressing coherent thoughts. Some may argue that it is premature to do so. Many of the newer curriculum programs encourage this exploratory phase. It does provide a way of letting students take ownership of the project.

Generally, after several sessions of working on these preliminary constructions, students need help in solving problems that have appeared and in deciding what steps to take next. In some cases, teachers may let them continue on their own, providing helpful advice but refraining from encouraging students to be systematic experimentalists. There is a point where students will reach a plateau. They make modifications on their preliminary constructions without achieving significant improvements. Continuing on this course eventually leads to frustration or loss of motivation to continue. Timely, helpful hints or explicit suggestions by the teachers can move them forward and result in improvements. Yet, these may be adopted without any sense of why they work.

Analysis of what is happening is neglected partly because each team has different constructions. In one type of possible scenario, the teacher would have to spend time with each team carrying out an extended discussion where the students examine what they have done. This is time consuming and requires special skills. In another scenario, there is some attempt at a whole class discussion where teams share their results. Since the constructions may often look different and lack comparable characteristics, the discussion can't go beyond a few of the common features. Given these circumstances, it is a challenge for the teacher to promote a deeper analysis of the design problems and develop a deeper understanding of relevant physical concepts. It is at this point when the teacher can introduce a second phase.

The Second Phase: Introducing a Standard Model

Students are asked to put aside their preliminary constructions and consider working with a *standard model*: a model that has been designed by one team or is suggested by the teacher. In both cases, the idea is to choose one that incorporates most of the features of all the other models that have been developed up to this point. This is a modified approach of what Kimbell et al. (1997), describe in their Key Stages in Modeling and Making (pp. 64–65). Alternatively, it is a model that will allow all of the teams to carry out a set of systematic experiments with the purpose of establishing a clearer understanding of how they can evaluate the most likely solutions to the posed problem. The teacher helps students isolate the most essential variables that can be tested. Controlled experiments are carried out to determine how these variables are related to the performance of the system they are designing. These experiments are followed by clear recommendations for improving the design of certain characteristics of the model.

Introducing the concept of the standard model has to be done carefully by the teacher. It has to be presented in a way that does not negate all the work done previously by the students. The teacher has to persuade the students that the standard model will build on what they have done, and allow them to get a better sense of what is possible and what works. This model should not be one that works so well that it forecloses any future development by the students; it should function well enough that consistent results can be obtained when experiments are conducted.

There are several advantages to introducing the standard model:

- It is a way of consolidating significant discoveries that have been made by teams in the open-ended phases of the investigation.

- It allows the teacher to move the students to carry out tests in a more controlled systematic manner.
- Since all of the teams are experimenting with the same model, results can be compared. Assuming care has been taken in the carrying out the experiment, the results will be more conclusive. There will be a larger amount of data collected so that patterns and correlation from this data will be more evident.
- Since all of the teams are involved, interpretations and explanations can be shared. The discussions will be focused, compared with a situation where each team carries out systematic experiments with their own particular model.
- Teachers are able to get at deeper issues regarding the physical working of the model. In order for the teacher to move students to a point where they are developing their own explanations and seeing the need for formal scientific conceptualization, there has to be a shared and highly focused experience.

These points are related to what Schauble, Klopfer, and Raghavan (1991) recommend and consider critical for helping students make explicit their thinking and in developing an appropriate model of scientific inquiry.

The Third Phase: Improving the Preliminary Models

Having spent some time working in this systematic way, students can shift back to a more open design process. They can incorporate their recently gained findings and conceptualizations into their preliminary models or go about coming up with an entirely new design. In either case, they will be working with a broader and firmer knowledge base and a more explicit understanding of the problem and possible solutions.

Taking this approach helps build up a knowledge base for the students. Design involves more than manipulation of materials and creative problem solving. The better the understanding the students have of the device, system, or materials, the more likely they can assemble a model that will meet or go beyond the original specifications. This phase has the same intent as the Key Stages of Kimbell et al. (1997), where they consider Design Issues and Evaluation. They give greater attention to the ultimate consumer of the products being constructed where here there is attention to the students attempting to meet the criteria given in the original formulation of the challenge.

Some educators will find this approach to be too restrictive of the students. It will be seen as taking away from the opportunity for students to come up with their own constructions and designs. To some degree, this is true. It may also end up possibly narrowing the designs of the final models. If the classroom teacher is very skillful and competent in inquiry teaching, he or she may be able to get each team to carry out the systematic investigations phase within the team. Discussion might be arranged to happen within each team. This is a great challenge. It is my sense of the contemporary situation that many elementary teachers are still just getting acquainted with an inquiry mode of teaching, and only a small percentage have done any real work in technology education. This holds, as well, for middle school teachers. Using a standard model approach can be a way of transitioning inexperienced teachers to a point where a class of students is taking multiple approaches.

Phases of Investigating Model Windmills

The pedagogical model of three phases using a standard model can be illustrated by following the development of a design project with model windmills. This is taken from one of the topics in the curriculum program, *Models in Technology and Science* (Zubrowski, 2001). Originally designed to promote learning about physical science concepts related to energy transformation, work, and power, it can be readily extended into an integrated design technology science project. The examples I will give of student's work are taken from a series of videos entitled *Windmills: A Video Case Study of and Extended Investigation in Technology and Science*, published by Education Development Center, Inc., 1999.

Open Exploration Phase

In the first session, students are challenged to build a working model of a windmill with a limited set of materials: eight index cards, four bamboo skewers, a small yogurt cup, an 18-inch thin metal rod, a metal tube (as shown in Figure 1), and a small fan for a wind source. They also have access to masking tape, staplers, and scissors. After viewing and discussing pictures of traditional windmills and making a rough sketch of a preliminary design, they are given the materials.

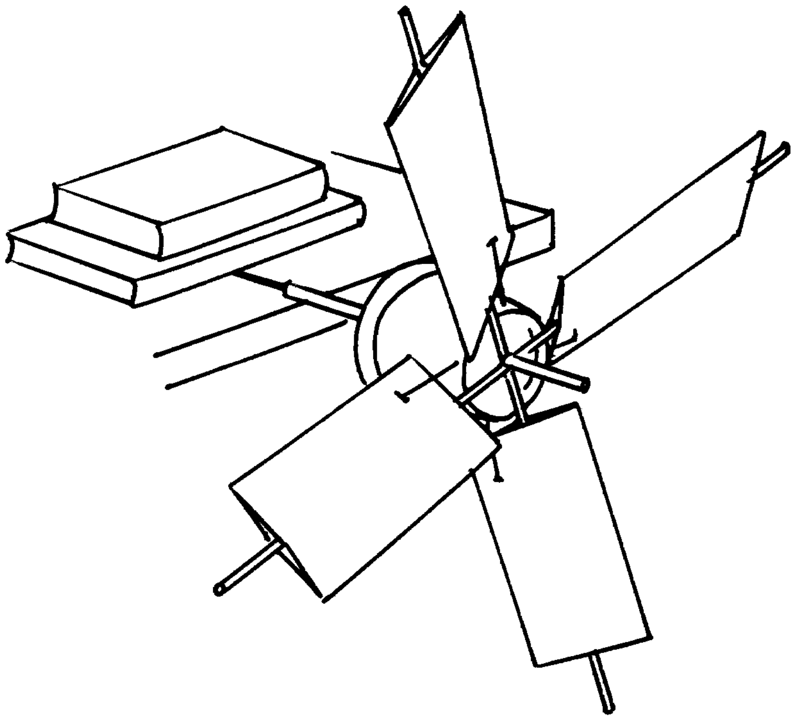

Figure 1. A standard arrangement of a working model of a windmill.

This problem has been presented to students with a variety of backgrounds and at different age levels. In most instances, they have been able to assemble a functioning model within one session. A second part of the challenge is to attach a string and cup to the rotating arms of the windmill so that it can lift weights. This will allow students to evaluate any changes they make in their models. The overall challenge is then to find ways of maximizing the lifting capacity of the model. It takes another session or two for students to find a way of attaching a string and cup to their models so that they can accomplish this.

Improvement of the design eventually centers on the number, orientation, and shape of the index cards attached to the bamboo skewers. In some ways, this may seem like a simple problem, but for elementary and middle school students, this project can go on for several weeks. From classroom observations of this project, the models they build during the first and second sessions barely function. Initially, students seem to be content with just getting something assembled that turns when the fan is pointed at the model. Their attention is totally given over to the construction rather than understanding how it might be functioning. Lots of sub-problems need to be solved within the overall problem of making the model function well. Students need to think about where to place the sticks on the cup that is acting as a hub, where and how to attach the cards to form the arms of the windmill, where to place the metal rod to allow the hub to rotate easily, where to place an axle, and how and where to hold the fan. Just solving these sets of sub-problems is challenging the full capacity of the students.

There are several important issues regarding this phase that are currently viewed from different stances. They are relevant to promoting an effective design process and in bringing out effective integration of science and technology.

- How many kinds and what amount of material should be given to students at the beginning of their exploration?
- How essential is this initial phase? Can it be eliminated or shortened so that the “real work” of creating a prototype is given the major amount of attention?
- How explicit and thorough a design plan can we expect from students before they even have explored with the materials?

The kind and amount of physical materials available to the students determines to a large degree what kind of project they can construct. In the case of the windmill model, they could be given a variety of small containers along with the yogurt cup, other kinds of paper and plastic sheets in addition to the index cards, and different kinds of rigid tubing. These added materials might have opened up the challenge, but they would also have increased the complexity. It is my experience in working with most students that providing them with lots of materials can overwhelm them. There is a tendency, particularly with elementary school students, to use up all the materials available to them. An underlying assumption for the students seems to be that if the materials were made available, then they were meant to be used. Students end up spending more time incorporating the materials instead of working on making their model functional.

What is relevant to this situation is the pedagogical principle of *manageable complexity*. The curriculum and the classroom teacher have to tune the challenge to the abilities, developmental level, and past experience, of the students. The more experience students have had with previous design projects, the more one can open up the challenge. If students are inexperienced, they need more structure. This can be arranged by limiting the type and amount of materials they will work with.

There is a need for a similar approach regarding the use of design briefs. To expect students to fully articulate how they would design and construct something before being given the materials is unrealistic. Unless they have done a great deal of construction activities at home or in previous school activities, they cannot anticipate all the problems that will arise. They need to play with the materials first, trying out different ways of joining them together. Particularly at the elementary and middle school levels, students have a real need to handle the materials to help them in their thinking. They need to put together the materials in a variety of ways, even if most of the resulting constructions aren't functional. They can see for themselves that certain arrangements just don't work. These comments run counter to some common presentations of the design experience. Charts in textbooks about design show that students should be putting together a design brief at the very beginning (Garrett, 1991; Hutchinson & Karsnitz, 1994). This is an idealized version of what can possibly happen with students at the elementary and middle school levels. Students have limited resources to anticipate and develop a full, realistic plan and solution unless they have had extensive experience with this process and know a lot about the particular device they are about to make.

This is not intended to preempt any pre-planning or preliminary discussions. The teacher can have students make some preliminary sketches, and have them discuss among the members of their team how they are going to proceed. There can be some preliminary research. In the case of model windmills, students can collect pictures of traditional and modern windmills. These can be used to help them form a plan of how they are going to assemble the materials given to them. However, there is still a need to recognize that some students “think with their hands.” In the dialogue with the materials solutions start to arise. These kinesthetic learners are often the ones who are the most inventive (West, 1997).

This beginning exploration is a critical one that often is undervalued and considered just an introductory phase before the real design or scientific learning happens. To some educators this phase is mere play. It gets students involved and acts as a motivator, but real learning does not appear to be happening. This issue is addressed in a series of videos called, "Learning to See.” These videos show elementary-age students exploring several different kinds of phenomena. When these videos are studied closely, the behavior of students reveals that play and exploration is purposeful. The manipulations of the materials and the students’ ongoing comments indicate they are very much engaged and thinking about what is happening, much of which is at a non-verbal level. Students begin to make their initial conceptions explicit only after this more open and informal experimentation (Karmiloff-Smith, 1992).

In the video series *Model Windmills* (Zubrowski, 1999), 4th grade students spent five to six sessions creating somewhat consistently functioning windmills. The index cards used as arms started out in a variety of positions and shapes on the bamboo skewers, which were pushed into the yogurt cup. Eventually, the cards were placed in a more symmetrical manner. In the first few sessions, students taped the cards to the skewers without anchoring the end of the cards to the yogurt cup. The moving air from the fan caused the cards to flap around, resulting in an inefficient transfer of energy. By the sixth session, the cards were securely anchored with pins to the yogurt cup (this refinement introduced by way of the teacher) and could be fixed at an angle so that flow of air hit all of them in the same manner. This resulted in more weight being lifted by the models. During this time, students intuitively made changes that were needed, but were not able to articulate verbally why they were making these changes. For instance, they knew in some way that adding many arms to the windmill was counter productive, but it wasn’t until the ninth and tenth sessions that they were able to articulate why this won’t work well.

The behavior in this first phase is mainly intuitive. There is a fair amount of trial and error. The main pre-occupation is to put something together that works. Therefore, discussions in this phase are mostly descriptive. There is a sharing of what works and what doesn't. However, embedded in these intuitive acts and vague descriptions are latent theories and the foundations for moving to next steps. It is short sighted and counter productive to force students to stop at this point or to assemble a final prototype.

Part of the role of the teacher during this time is to help students get their models in some kind of effective working order. The goal during the later part of this phase is to concurrently improve the working of their models while also reflecting on the manipulations and the resulting change in results. Many kinds of questions can be asked at this point. The well-prepared teacher already has a sense of how the model is functioning, what some typical problems are that students encounter, and what kind of conceptions they bring to their understanding of how the device works. Using this essential background, well-formulated questions during this phase can be a subtle way of directing their attention and pointing out the importance of the observations and discoveries they are making. There are times, also, when occurrences can be exploited to move students to think conceptually about what they have just seen occurring. For instance, sometimes students will have a puzzled look on their faces. At moments like this, students can be highly motivated to puzzle over and attempt to come up with explanations. In the early phases their comments and explanations may not be well formulated, but they shouldn't be dismissed because they can be returned to later in the investigation.

Standard Model Phase

Exploration with the materials will reach a point where students have arrived at a consistently functioning windmill, but they aren't sure how to go about making further refinements. In the video "Windmills," one team of students was lifting 120 nails while other teams barely lifted 40. The other teams did not realize that the angle at which the arm is oriented on the cup can make a difference in the lifting capacity of their models. Often, another intuitive act is to place the fan on the side of the model instead of in front. This placement can make a real difference in the performance of the model. Students need help in seeing the significance of these discoveries, and they need to expand on these discoveries in a systematic manner. This calls for setting up controlled experiments. Shifting to this kind of context provides for the teacher an excellent opportunity to have students make explicit and discuss science concepts that are embedded in these more formal experiments**.** This is the kind of sense making that Schauble, Klopfer, and Raghavan (1991) propose as a necessary practice if students are to gain a greater awareness of scientific method as well as concepts. These discussions can help in their understanding of how a windmill functions which builds a larger knowledge base. This, in turn, gives them a better sense of ways to improve their original design.

When the teacher observes that students are not moving forward or are mainly operating in a trial-and-error mode, there are two approaches that can be taken:

1. The teacher can consult with each team and help the members plan out a series of experiments with their own preliminary model. The teacher can help them sort out the most salient variables and work out the experimental method by which they are going to be examined. If students have had extensive experience with design challenges and the inquiry process in previous years, this approach may be workable. However, if students are fairly new to independent work of this nature, it may result in inadequate and incomplete experimentation.
2. The teacher can have all the teams work with an agreed upon model that incorporates the salient characteristics of most of the preliminary models that have been constructed up to this point. The teacher needs to assure students that they will return to their preliminary models to continue to work on them after this beneficial, transitional phase. This step is not meant to negate their designs, but rather to help them think about what features contribute most to an effective windmill. This means maximizing the lifting capacity of the model.

Recall the study conducted by Childress (1996) previously mentioned. He speculated that students may have had difficulty transferring results from an experiment with one kind of model windmill to those they were constructing of their own design. What I am recommending here is that the experiments be conducted on a model using the same materials and of a similar construction as those already being used by students. Here, results are directly applicable to the students' own designs.

Once a standard windmill model is decided upon, there are several characteristics that can be investigated. Most of these involve the number and shape of the arms. Students can evaluate how the lifting capacity of their model changes as they go from 2, 4, 6, 8, and 10 index cards functioning as the arms of the windmill. They can also determine the best angle at which the cards should be set to align with the direction of the airflow and achieve the best lifting capacity. They can test to see whether placing the fan in front of the windmill gives better results compared with having it at the side. In each of these experiments, the teams share their results. If some care is taken, they will find that 45 degrees is the best angle for the orientation of the arm of the windmill, and that 8 arms is the optimum number to use. They will also find that the optimum placement for the fan is directly in front of the windmill rather than at the side. Establishing these conditions results in a significant difference in the lifting capacity of the model windmill. Initially, students have models that lift 30 to 40 nails. When changes are made in the above-mentioned characteristics, the model can now lift 140 nails. Students are very impressed by this difference.

By having all the teams carry this process out in a systematic fashion, they have the opportunity to share their results. Because similar results are obtained among the teams, there is greater confidence in the discoveries. More important, there is the opportunity to discuss why these changes made a difference in the lifting capacity of the windmill, opening up a discussion of science concepts. The teacher can challenge students to think about and discuss how the energy of the moving air is transferred to the arms of the windmill. With older students, some of the physics principles of work and power can be introduced. This becomes relevant when considering the kind of function a windmill will perform. The goal of these discussions is to have students reflect upon and analyze their results and connect them to basic scientific concepts. In this sense, the design process and science become intimately intertwined.

There is another added value for taking this approach. The systematic experimentation and careful consideration of the results provides a model of a *process* for the students. It shows them how they can carry out the same process with other kinds of design projects. When they return to their own preliminary models, they can utilize this process when making further changes. From a pedagogical point of view, the example with the model windmills illustrates that process can't be separated from content. If students experience this same kind of experimentation with a standard model in a number of specific contexts, they are more likely to gain a sense of a generic design process. Some writers have argued that students are more likely to develop these higher level cognitive skills by working through specific contexts than if these general skills were taught in some kind of direct didactic manner (Keil, 1991, p. 231). Using a standard model is one way to promote this kind of learning.

Culminating Activities or Explicit Consolidation of Findings

Having established some essential features of an efficiently functioning windmill, students can return to their preliminary models. At this point, they can be asked to be more detailed and thoughtful in revising their design briefs. They can make changes to reflect what they have learned from the standard model. In the situation with model windmills, further refinements can be made that might improve performance. For instance, they can experiment with different-sized arms. Up to this point, they have been using 4" x 5" index cards. Will there be a difference in lifting capacity if students use the same total surface area but they use a greater number of smaller arms (e.g., students can compare a windmill using four 4" x 5" cards with one using eight 2" x 5" pieces of cards)? Will it make a difference if the cards are twisted into a propeller shape? Will it make a difference if the length of each arm is made longer? These and other refinements can be considered. Each of these can be evaluated by carrying out systematic experiments. At this point, the teacher can also introduce new materials and a larger, more powerful fan. The challenge can be revised to reflect the addition of these materials. The overall design process can culminate in a final prototype after all of the different options have been considered. A formal presentation of their prototypes can also be included in this process.

During this last phase, there is also an opportunity to carry out some kind of embedded assessment. For instance, in one situation, the teacher presented her class with three, special model windmills after ten sessions. In appearance, they looked similar to the ones that the students had been using. However, they had been changed so that they did not function efficiently. The students were asked to determine by inspection and operation of these models what was wrong with them. One of the models had a relatively simple change. The rubber band holding the cup to the metal tube was removed. Although the body of the windmills was turning, it was not lifting the cup of nails The use of the rubber band was not apparent to the students in the first two to three sessions. In fact, it wasn't ever explicitly talked about in any of the sessions. However, most students noticed very quickly that it wasn't there. One of the three test models had a change had a change so subtle that it would not have been noticed if the students had not done extensive work with the windmills. The blades on the windmill were at a 45-degree angle to the skewer as they had been with several of the experiments the students had done. However, the orientation was reversed. This kind of arrangement of the blades does not work. The fan blades and grill cause air to rotate slightly in a counterclockwise movement, as shown in Figure 2. Some students noticed this difference and knew it was the reason why the windmill was not working efficiently.

Most of the students noticed what was wrong with each of these models. If they had been given these same models after the third or fourth sessions, they would not have had the experience to recognize the teacher's changes, especially regarding the windmill with the reversed blade orientation. The combination of observing what students do after discussions in changing their models, and presenting them with the challenge of analyzing poorly functioning models, are ways of assessing what students have gained from the activities.

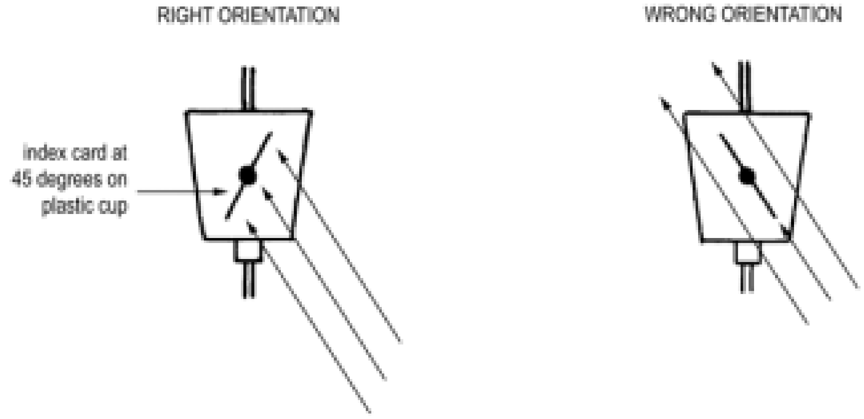

Figure 2. The right and wrong orientations of the arms of the windmill in relation to the air coming from the fan.

The overall process for windmill design using three phases and a standard model can be applied to other kinds of design projects: model water wheels, mechanical clocks, structure projects, different kinds of model vehicles, and related transportation models. These are all highly engaging projects and offer a rich context for both design and inquiry. As illustrated by the windmill investigation it is possible to direct students' attention to a deeper consideration of how a system functions in such a way that it increases their understanding of the system and at the same time enhances their understanding of scientific process and concepts. Working toward an effective final design provides the motivation to carry this out. Using the process outlined above helps the teacher to get at critical thinking skills that have been put forth by a variety of researchers and educators as essential if students are going to move beyond the mere act of making something and gain a sense of understanding at a metacognitve level of both the design and inquiry process. However, even if the form of this overall process is carried out it is still highly dependent on the sensitivity and skills of the teacher to help students make explicit their learning and truly benefit from this approach.

Issues and Realities

There are a number of issues that arise when attempting to bring about the kind of integration being presented here. Full integration requires close collaboration among teachers and dictates that students see the connection between subjects. In a survey of demonstration schools in Missouri, Nebraska, Colorado, and Oklahoma County School Districts, Wicklien and Schell (1995) found the following kinds of problems. The teacher team had difficulty working together. Some had problems committing to integrated projects. Students had problems seeing the connections between science, math, and technology, and in one situation, resisted a multidisciplinary approach. These findings suggest that integrated projects require a lot of planning on the part of the teaching team and that there is a need for a consistent pedagogical approach. When students experience an integrated project only occasionally in the midst of completely separated subject matter teaching, they have difficulty making the switch especially as they reach middle school. In a sense, the problem goes beyond teachers and students because it requires a restructuring of the school year and school culture.

Then there are two very important concerns regarding this three-phase process that will probably be expressed by some educators. One is that this approach requires weeks, not days, to complete. In the current push to cover all of the standards, do teachers have the time to carry this out? Another is whether this approach is really a design technology project, or is it a science topic using a technology context?

First, the approach being promoted herein needs to evolve over a period of several weeks. It takes this amount of time for most students to become thoroughly acquainted with the full challenge or problem, sort out the essential elements, and figure out how to test in a systematic way to obtain clear results. Building up this knowledge base, in addition to constructing an effective prototype, takes a fair amount of time. This kind of investment in time and effort will result in a more satisfying experience for the students, both in terms of affective and intellectual domains. The satisfaction is real, because they will have constructed a functioning model that gives measurable results. At the end of the investigation, they will also have seen progress both with techniques and understanding.

Despite calls at the national level for greater in-depth learning with fewer topics, this sensible recommendation is not being implemented at the local level. Teachers that I have worked with see the need for spending more time with a topic, and would like to develop topics in this manner. However, both the newer state frameworks and the current type of testing at the state level place teachers in a difficult position. They are accountable for making sure students do well on the tests. If the tests are designed to cover many different topics, teachers are forced to cover the same, however well this can be done in the time allotted for each topic. Until there is a paring down of standards at the state and school district levels, and a revision of assessment techniques to reflect this changed emphasis, classroom teachers will be unable to give students a richer and deeper learning experience.

Second, most science and technology educators would consider working with a standard model as I have outlined the process. The topic of windmills - as well as topics such as water wheels, vehicles, and clocks - is certainly part of the technological world. What is mainly at issue is the relationship between a design activity and the development of scientific understanding. I am proposing that design projects at the elementary and middle school levels will be much enriched and put on a firmer pedagogical foundation if there is an infusion of science process and content. Care has to be taken that the science doesn't take over the design process. On the other hand, science teaching will be greatly enhanced if it occurs in a design technology context. From my observations and teaching experience, students are highly motivated when working on a challenge or problem that is related to their personal lives or the world outside the classroom. This kind of context establishes a reason for developing explanations and attempting to understand how something works.

Finally, the example developed here is mostly related to one type of engineering and design project where it is difficult to bring into consideration the needs of a user or a relevant context. In the case of windmills, they can be related to the need for alternative energy production, which is currently receiving renewed attention. This makes it more relevant but still doesn't move students to incorporate user criteria into their design process. One way of dealing with this problem is to recast the challenge. For instance, in the Society of Automotive Engineers' *World in Motion II* (1999) curriculum, middle school students were challenged to design a toy vehicle for a fictional toy company and a set of plans for flying toys for a fictional publishing company. In the former, they were supposed to survey younger children in their school collecting information about the children's preference for toy vehicles. In the latter, results from a national survey on children's spending habits and toy preferences were provided. Students were to use these surveys in their assembly of a final prototype. This added another level of complexity to the overall design process but gave a greater relevance to it. However, it also meant additional time to fully utilize these results.

All of these issues suggest that science and technology teachers at the middle school level should move toward closer collaboration and develop ways of working on joint projects. There are big political and logistical obstacles to overcome, but it would seem to be worth the struggle. At the elementary level, teachers have more flexibility and may be more open to an integrated approach. Education and administrative support will be needed to help teachers consider such an approach and to develop the knowledge base to carry it out effectively.

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