Strategies for supporting student inquiry in design tasks

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Abstract

Design projects are rich contexts where students may apply scientific inquiry to develop and test explanations for their design's performance. These contexts may serve as opportunities for students to develop skills that are traditionally difficult to master, such as generating experiments to test hypotheses and using evidence to support one's reasoning. However, the goal of producing a successful design often leads students to focus on improving their design at the expense of developing scientific explanations, even though such explanations could inform later designs. A challenge to educators is to identify and implement strategies for supporting design tasks that enable students to develop and defend scientific explanations for their designs.

Much of the strategic support that focuses student reasoning lies in the interaction between teacher and student. In this paper, we explore three teachers' strategies for supporting student inquiry using engineering design tasks. We describe how each teacher frames the task and provides guidance during design work to help students pursue experiments to evaluate designs, apply scientific principles to improve designs, balance engineering and scientific goals, and cope with the complex nature of open-ended design projects.

Introduction

There is currently much interest in the science education research community in engaging students in scientific inquiry, which is thought to be a more authentic and effective learning context for scientific principles (Linn, diSessa, Pea, & Songer, 1994). However, while many researchers are now developing learning contexts more suited to inquiry, few existing curricula (e.g. textbooks) provide truly open-ended inquiry, where students generate investigations to explore questions that they define (Germann, Haskins, & Auls, 1996). New curricular contexts for supporting inquiry are needed.

Engineering design tasks, where students attempt to design an artifact to meet a specified need, may be useful contexts for student inquiry. In these tasks, students engage in scientific inquiry to increase their scientific understanding of the factors which influence their design. What they learn allows them to improve their design.

There are several reasons why design contexts may be well suited to inquiry. Design tasks are situated in real world problems, which allows students to draw on their own experience as well as their scientific understanding (Bucciarelli, 1994; Roth, 1996). Designing artifacts to meet specific needs helps to focus student-driven inquiry on specific questions related to their designs. Tangible design goals create a practical purpose for scientific understanding because students can apply what they learn to improve their designs (Perkins, 1986). Rarely is there one ideal solution, which allows students to pursue their own ideas. Students must determine the means for evaluating the success of their design, which often results in empirical tests which

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generate data students use to reason about design performance. Students may draw on these results to reason about and iteratively improve their solution over time.

The challenge of teaching inquiry through design

Situating inquiry in design contexts raises a number of challenges for teachers. While aspects of the design task provide opportunities, or invitations, for inquiry, the design task itself does not directly support student reasoning during inquiry tasks. Scientific inquiry can be difficult for students. Students who engage in inquiry often have trouble designing experiments to test their hypotheses, and have trouble using data to support their arguments (Klahr, Dunbar, & Fay, 1990; Kuhn, 1993; Schauble, Glaser, Duschl, Schulze, & John, 1995). Further, the purpose of scientific inquiry can be opaque, as students often view what they learn in science class as unrelated to the way things work in the real world. Students may not see the value of applying their understanding of scientific ideas and principles to their design. Teachers must find ways to address these concerns if their students are to engage in successful inquiry.

Design also raises its own set of challenges. The ill-structured nature of design tasks presents students with a wealth of possible design decisions, each of which may have an impact on their design's performance. Designs must meet real world needs, which are often complex; evaluating design performance may involve considering multiple factors, such as strength, weight, and cost, which vary in different ways. The complexity of design projects also means that students frequently must address unexpected, emergent problems that arise once they begin building or testing their designs.

Engineering design and scientific inquiry also have complementary, but distinct, goals. Design focuses on constructing solutions that meet specified needs. Design problems create a need for knowledge, which may be acquired through scientific inquiry. Inquiry focuses on developing a conceptual understanding of different design factors. This understanding can then be applied to inform design decisions. However, it is possible to improve designs without understanding conceptually what makes a design work, and students frequently fixate on design performance at the expense of developing their understanding (Schauble, Klopfer, & Raghavan, 1991). To engage in inquiry, students must balance their focus on improving design performance with a focus on developing their scientific understanding.

Situating inquiry in design contexts has promise, but is no panacea. Design will prove an effective context for inquiry only if students have both opportunity to engage in inquiry and support to address the challenges students face when pursuing inquiry. Further, the challenges that design poses must be addressed.

How do teachers support student inquiry during design?

Students engage in inquiry within a classroom context co-constructed by the teacher, the students, and the instructional materials (Ball & Cohen, 1996). However, the task of providing support for inquiry in these settings falls primarily upon the teacher, who has the responsibility, and the opportunity, to frame the activities in which students participate and provide guidance and coaching throughout the design process.

In this paper, we will discuss the strategies teachers employ to support student inquiry in design tasks, focusing on three classrooms in which teachers used design projects as a context for inquiry. These projects reflect a particular curricular model for supporting inquiry through design. Our research questions focus on understanding strategies that help students address the following challenges related to both inquiry and design.

- *Connecting design decisions to scientific principles.* How do teachers help students apply their scientific understanding to improve their designs?
- *Generating evidence to reason about design decisions.* How do teachers help students construct good experiments and reason about experimental results in a scientific way?
- *Managing design complexity.* How do teachers help students cope with emergent problems and reason about how design decisions may affect multiple performance criteria?
- *Balancing engineering and scientific goals.* How do teachers keep students focused on developing explanations for design performance?

A curricular model for inquiry through design

We have developed several curricular modules for high school science classrooms that attempt to engage students in inquiry through design projects. The modules, part of the Materials World Modules research project, are based on a model we term *inquiry through design* (Baumgartner & Reiser, 1997). This model for curricular design seeks to create opportunities for students to pursue inquiry in design settings, while providing curricular support for the inquiry process. Curricula based on inquiry through design consist of three main components.

- A series of *staging activities* provide students with background ideas and principles which they may apply to their design.
- A *design challenge*, which may be posed by the teacher or the students, asks students to propose and build a design to meet a specified need. Students typically build a series of designs in order to evaluate the effect of different aspects of their design.

- The final component is a *redesign*, where students apply what they have learned from both the staging activities and their initial design efforts to improve their own design. An opportunity to redesign allows students to explore alternative designs and then use what they learn to produce an optimal design, rather than targeting an optimal design from the beginning.

For example, in the *Composites Module*, students are asked to design a prototype fishing pole, based on a drinking straw, that is strong, flexible, and lightweight. The design project typically runs two to four days. The goal of the project is not only to produce a good design, but to be able to explain how the materials and the construction of the design contribute to its performance. Students draw on earlier staging activities in which they gained experience identifying different composite materials, explored the nature of strength and stiffness, and tested different materials' properties of strength and stiffness in order to design and build prototypes that meet the stated criteria. Students must not only identify potentially useful materials, but also decide how to incorporate them into their design, and generate evidence to support their explanations for why their designs work.

Curricular support for student inquiry is provided through guiding questions, posed by the written activities, and structured design journals that emphasize explanation and prompt students to focus their experimentation on explanation as well as performance. Suggestions for assessment downplay tying student grades to the performance of their designs, focusing instead on how well students engage in the process, and the strength of their final explanation for why their design works.

Exploring teacher support of inquiry in design contexts

While these curricular units are designed to structure the design project in a particular way, they are only one factor that contribute to the design context as it is enacted in the classroom. Teachers who choose to use design curricula in their classrooms do so with specific goals in mind. These goals, which affect how the teacher presents the material and how the student perceive the material, may or may not align well with the set of goals the curriculum designers had in mind. Often, the result is the use of inquiry-based activities in ways that do not support inquiry (Germann, et al., 1996; Olson, 1981; Welch, 1981).

On the other hand, teacher enactment may enhance innovation. A written curriculum is, at its heart, a didactic medium which cannot interact with teachers or students. Such a document cannot completely specify what should occur in a classroom, especially a classroom structured around open-ended inquiry. That leaves substantial portions of instructional practice — including coaching, scaffolding, and fading strategies — open to teachers' interpretation. For example, the Materials World Modules provide general suggestions about assessment, but no specific rubrics. Teachers must design their own measures to evaluate their students' performance.

In fact, one can think of the task of teaching one of these modules as a design challenge in itself: the design of enactment to support student inquiry. Because of the underspecified nature of the written curriculum, we have opted to encourage teachers to adapt inquiry through design to their own instructional practice, so that by observing teachers who successfully engage their students in inquiry, we can document specific teaching strategies for supporting inquiry and so begin to construct a model for how different teaching strategies support student inquiry in design contexts. Such a model will be useful for incorporating support strategies within the written curriculum, as well as providing other teachers with examples of teaching practice that contribute to student inquiry.

Our analyses of teaching strategies focus on two specific aspects of enactment: how teachers frame the design task for their students, and how teachers provide guidance during the design task.

Framing the task. The framing of the design task is important because it defines the nature of the task students face. Depending on how the task is presented, different aspects of design that afford inquiry may be accentuated or diminished. As an example, consider a design task which does not include a redesign phase. Such a task may provide less motivation for students to learn from their design, because they will not have an opportunity to apply what they learn.

Teachers also frame the task by communicating their expectations for student work, often in the form of assessment measures. Some teachers may base student grades on design performance; others may emphasize being able to explain why a design works. In this way teachers influence student goals for the project, which in turn influence the degree to which students engage in scientific inquiry.

Touring and support strategies. Teachers provide support for student inquiry throughout the design task. In open-ended, student-centered classrooms such as these, many teachers tour the classroom, moving from group to group in order to monitor group progress, reiterate expectations and provide guidance. These interactions while students are engaged in the design task allow teachers to help students manage the complexity of the design project, deal with emergent constraints, and reason about design decisions, connecting principles from the staging activities as well as evidence generated from earlier to designs to bear on the problem.

Teacher support for student inquiry is a critical aspect of the classroom enactment. Examining the classroom through the lens of these two aspects of enactment allows us to study how teachers provide opportunity for inquiry as well as how they help students to take advantage of these opportunities. Indeed, these two aspects may be two sides on one coin, for without opportunity, students may never attempt inquiry, while a lack of support during the inquiry task may leave students floundering in the complexity of the task. We will examine the way in which teachers employ both of these classes of strategies to address the challenges students face during inquiry: connecting design decisions to scientific principles, generating evidence to reason about design, managing design complexity, and balancing engineering and scientific goals.

Method

This study is based on three cases of classroom enactment of design curricula. In each case, the teacher used curricular units from the Materials World Modules projects, units developed around the principles of inquiry through design described earlier. The three teachers represented in these cases, Laura, Renee, and David, each succeeded in engaging students in inquiry in different ways. Our goal for each of these cases is to understand how the decisions that the teacher made affected student engagement in inquiry.

After providing some contextual background information about the teacher and the class, we will describe how each teacher framed the design task, the nature of the teacher's touring and support strategies, and how these aspects of the enactment contributed to student engagement in inquiry.

Following the three case discussions, we will discuss particular aspects of inquiry support that occur across classrooms, and compare the different manners in which these three teachers addressed similar challenges. Each of these teachers made decisions that led to particular tradeoffs in terms of time, the teacher's goals for the module, and student engagement in inquiry. Our goal is to use these cases to begin to build a model that explains how different support strategies contribute to inquiry within design contexts.

Data

A researcher was present and observed in each of the three classes. In addition to field notes, we videotaped whole class discussions and small group work. To better understand how various student design decisions impacted the design process over time, we focused on specific groups and followed these groups throughout the design project. (Group selection was negotiated with the teacher, with the goal of picking a group of students that were fairly representative of the class.) Students from these focus groups were interviewed following the module, and we held ongoing conversations with the teachers to document their perspective and what they saw as the benefits and obstacles of the module.

In all classrooms the researcher adopted a non-teaching role and offered suggestions about classroom practice only when directly asked by the teacher. We chose to adopt this more neutral stance because we were interested in seeing how teachers adopted the modules to fit their own practice, and what strategies emerged to support student inquiry in this context.

Results

Scaffolding experimental design: Laura's classroom

> *Laura is a co-author of the Composite module and is familiar with the pedagogical model embedded within the written materials. This case explores how she provides support for student experimental design, so that students may generate scientifically credible data to reason about their design. The case is also interesting because Laura devoted very little time to the staging activities, preferring to spend the time she had on the main project design and redesign.*

Background

At the time of this design project, Laura was a fourth year chemistry teacher in a suburban Chicagoland high school. She used the Composites module in her regular level sophomore/junior chemistry class. Laura is the co-author of the Composites module and had taught the unit twice within the past year. She had also used activities from a draft version of the curriculum even earlier than that, although those activities bore little resemblance to the ones that comprise the current curriculum.

The module was used just before winter break as the culminating activity for a six-week unit on petroleum. All regular level chemistry classes, including two taught by Laura, used the module at this time.

The observed class was an early bird class, which means it met prior to first period for fifty-five minutes, the length of a regular science class. The class was rather small, consisting of only ten students, nine of whom were female. Students worked in groups of three that Laura assigned. The focal group for this case consisted of two girls, Sarah and Kelly, and the sole boy in the class, John. The groups worked together during the staging activities as well as the design project. For the design project, the group turned in a single design journal for assessment.

Goals

Laura's goals for her students centered around the idea of working collaboratively and doing something on their own, without teacher direction. In an interview prior to the start of the module, she described how it was important to her that students take ownership of this project.

> I want the student to feel like this is something that they figured out how to do. They're going to make their own fishing pole, it can be whatever they want, and then they're going to test it, and then they're going to make it better. You know, this is theirs. They've designed it themselves.

At the same time, Laura was concerned that students would need help to be able to succeed in this project. While she felt that it was very important for students to be designing their own investigations, she felt that was also very challenging — "almost impossible" without a lot of help from the teacher.

In addition to focusing on the student-directed nature of the project, she emphasized the importance of collaborating both within groups and within the class. She viewed such collaboration as an aspect of scientific communication, and an opportunity for students to share information with one another. Speaking here in an interview prior to the start of the module, Laura foresaw several opportunities where communication would be important.

> As far as communication skills, they'll have to present their proposal at the beginning to the rest of the class to exchange ideas and they'll also have to communicate within their group in order to make one proposal. And then at the end they'll need to present to the entire class what they did and why they did it and how their redesign worked.

Framing the task

The Composites module, as written, consists of four staging activities followed by the design project. (A optional fifth staging activity is included in an appendix of the teacher's edition.) Taken together, the staging activities, design project, and redesign are expected to take between one and two weeks of class time.

Laura planned to do the module in six days. To make it fit, she dropped one staging activity, an activity where students explored the difference between strength and stiffness, and covered the remaining three during the first day. The first, an activity where students "hunt" for composite materials at home and elsewhere, was assigned for homework the evening before the first day; students spent about twenty minutes in class sharing their findings and refining their understanding of what composite materials are and why they are used.

The second activity was a quick hands-on demo where students observed the effect of reinforcing ice with shredded toilet paper. The purpose of this activity was to demonstrate that a composite material could have properties that were better than either material alone: in this case, the strength of the ice/paper composite was greater than that of the plain ice.

In the third activity, students explored the effect of bonding on composite properties. Composite materials are formed of multiple materials that are bonded together; if materials are not bonded or are poorly bonded, they may not perform as well. In this activity, students experimented with short lengths of insulation foam that had been reinforced with cardboard. In one case, the cardboard was not completely glued to the foam; students observed that because of this defect, this composite was not as stiff as the others.

Towards the end of the first day, Laura introduced the fishing pole design project, which is to design a prototype fishing pole, starting with a straw, from composite materials. She led a discussion in which the students generated the criteria they would use to evaluate their designs: strength, flexibility, and weight. She gave the students three days to design, build, and test their initial designs. As part of their designs, students were instructed to identify one variable which they would explore by building a set of designs. The purpose of having a variable was to keep students varying only one thing at a time, so that the data they generated would speak to the effect of that one variable. As Laura put it, "if you start varying a whole lot of variables at a time, it gets confusing." Students were still allowed to make multiple changes to their design—for example, reinforcing the inside of the straw with wire or wood and reinforcing the outside of the straw with tape—but the set of designs that the students built needed to share all of these changes save for the one variable.

During the second day of the module, Laura handed out her grading rubric (see Appendix A) and went over it with her students, explaining what she expected in each of the rubric categories. What is interesting about this rubric is the absence of design performance from the student's grade. Students were not graded on how much weight their design held or how flexible it was, which were the two main performance measures students used to evaluate their design. Instead, Laura explained how their grade was to be based primarily on how they engaged in the design process, including their ability to use the design task to investigate a question, make predictions about that question, and reconsider their predictions in light of their results.

The rubric also emphasized the redesign, which took place over the final two days of the project. Students were encouraged to take what they had learned from their first set of designs and apply it to their redesign. Students learned from their own designs as well as those of others; groups presented their designs to the class prior to redesign. For the redesign, as with the first set of designs, students were instructed to define a variable to explore. For example, one group's first design explored the optimal amount of telephone wire to place inside the straw for reinforcement. Having learned that two lengths of wire, about the maximum that would fit, was best, the group began their redesign with two wires inside the straw as part of their design. In their redesign, the group explored what aspects of the wire, itself a composite material, contributed the most to the design.

Touring and coaching strategies

Framing the design task for students is one way in which teachers can structure student engagement in inquiry. Teachers also support student inquiry while students are working on the design task. Laura toured her classroom almost constantly. Unlike some teachers, who often return to their desk or to the front of the room between trips around the classroom, Laura was continually moving among groups. In a class as small as this one, where there are only three groups, the frequency of her visits was accentuated. She often returned to a group only two or three minutes after she last saw them. Students rarely interrupted Laura's touring to ask her questions, although given the frequency of her visits, this isn't surprising.

When she toured, Laura tended to initiate interactions with a group of students by asking a question like "How's it going here?" or "What do you guys think?" These questions led to short discussions of a minute or two where students reported on their design and explained what they were planning to do. During the latter stages of the project, especially the redesign stage, Laura initiated fewer conversations while continuing to tour. In these cases, she often just listened to the group for a few seconds before either moving on or asking a question.

Laura usually had specific goals for these interactions that went beyond simply monitoring group progress. Two main goals related to students' use of variables in their design and the importance of bonding to composite materials.

Laura questioned the focus group about their variable several times while they were proposing and building their design. She was concerned that students had their experimental design in place before they began to build their designs, so that they would be able to generate useful evidence. In fact, students had to check off their design proposals with her before they could begin building. The following exchange is an example of a touring interaction from the second day, after the group has decided what to do but before they have begun to build their designs. Laura was visiting each group to find out what they were predicting their designs would do.

TEACHER	OK. So what do you guys think?
JOHN	We think that ours is going to be very sturdy because we're going to use telephone wires.
TEACHER	OK. Remember our goals are strong and flexible. OK? So... so you're going to have five different straws that you make. What's the difference between them?
SARAH	(pause) There's...
JOHN	(pause) ...difference between them?
TEACHER	What's your variable?
KELLY	Um... number of... well before it was number of pipe cleaners, but we changed that.
TEACHER	OK. So now what is it?
KELLY	I guess, it's got to be something with the phone wires, I guess.
TEACHER	OK.
JOHN	(pause) Amount of phone wire?
TEACHER	Amount. OK. What does that mean?
SARAH	Like, maybe length, or... we doubled it.

TEACHER	OK. So the number of times you put the wire through?
ALL	Right.
TEACHER	Number of wires that go through?
SARAH	How many times do we have to have a variable?
TEACHER	(pause) Once for right now. We are going to go back and have a new variable... when we do our redesign, but for right now we have one variable, going over five straws. (pause) So you're going to make five straws. Each of which has a different amount of wire inside.
ALL	OK.
TEACHER	OK? So, which one's going to have... which one's going to be the strongest? ...two goals, right? Strong and flexible?
JOHN	Yeah.
ALL	The bottom.
TEACHER	The bottom? What, what do you mean, the bottom?
KELLY	Like, the bottom straw, the first straw.
SARAH	No, the...
TEACHER	The straw that has the most wire, or the straw that has the least wire?
ALL	Most.
TEACHER	The most wire? And which one will be most flexible?
SARAH	The one with the least.
TEACHER	OK. Which one will be the best fishing pole? Because we said we wanted our fishing pole to be strong and flexible.
JOHN	The middle.
TEACHER	The middle? Is that what you (KELLY) think too? Ok. Ok, whose writing is this?
KELLY	Mine.
TEACHER	Ok. So John's going to write today? You can write down your predictions.

This example illustrates several aspects of Laura's touring style. First, she elicits the group's predictions—the main reason for this touring cycle. Then, she moves on to focus on the group's experimental design. What are they varying across their five designs? The group has trouble describing their variable, because they had just come up with a new design, using telephone wire instead of pipe cleaners, and had not addressed the new variable yet. Laura coaches them through the process of defining their variable, primarily by asking questions and restating or revoicing their responses. At the end of the exchange, she encourages the students to document their thinking in their lab book.

Laura also provided examples of experimental design for groups to use as analogies. On the second day, when students had begun to build their designs, she toured the class, carrying with her an example from the previous year. While students had already proposed their designs and identified a variable to explore, the example provided students with a model of good experimental design. The example also illustrated that student designs could incorporate more than just the variable, a point particularly relevant to the focus group, which had decided not to use any form of tape around the outside of their straw, despite a short conversation about considering tape from the day before.

TEACHER	I want to show you a design that was used last year. It's different from any of the designs that we're using in here, but the idea is that they put the same number of pipe cleaners inside, and they wrapped one layer of plastic wrap around this one, two layers around this one, three layers around this one, and four layers around this one. So that's the kind of thing you want to do.

Laura tried to help students apply their scientific understanding to their design, specifically that how materials are bonded together greatly affects their properties. She repeatedly reminded the focus group that they needed to bond their materials to the straw in some way. She pointed back to the staging activity they had done which showed that a foam composite that had not been completely bonded together was not as stiff as other foam composites that were completely bonded.

TEACHER	Remember, when we're making a composite we want to somehow get those things to be bonded together. So how are you going to get the pipe cleaner stuck to the straw?

Rather than making the conceptual leap from the role of bonding in the staging activity to the role of bonding in the design project, students appeared to accept this suggestion as another design constraint, without understanding that bonding materials to their straw might improve their design. In follow-up interviews describing their design, students mentioned the glue that they eventually used to bond the telephone wire to the straw, but explaining its presence only in terms of necessity (“we poured glue down the sides because it had to be attached to the straw somehow”) and not causality.

Discussion

Students in Laura’s class were able to generate evidence they could use to reason about their design. The emphasis on incorporating a single variable into each set of designs, combined with the guidance Laura provided as she toured the room, resulted in groups designing experiments that they could use to test their ideas. Although students often had strong expectations about the effect of their variable, they weren’t always correct. For example, the focus group was surprised to discover that their prediction for the most flexible fishing pole in their first set of designs was wrong. This finding led the group to focus their redesign on finding out what made their most flexible design work.

Students were less successful at drawing on scientific principles from the staging activities to inform their design. Students seemed to incorporate bonding into their designs at Laura’s behest, rather than through a conceptual understanding of bonding’s role in composite materials. However, students from the focus group, when asked to explain their designs in follow-up interviews, did mention that they had used glue as part of their design, and described its purpose as attaching the different design materials together. It may be that since Laura spent very little time on the staging activities, the students had not developed enough of an understanding of the role of bonding to be able to apply it later, especially in a more abstract way. The foam beams from the earlier activity were bonded together layer by layer; it was possible to see the disjoint directly. The designs the students made frequently reinforced the inside of the straw. Because the straw was opaque, students could not see that their materials might be moving independently from the straw during testing.

Finally, students in this class displayed very little competition during the design project, a factor that Laura appreciated, although she wasn't quite sure why it had happened.

> I think it was because I encouraged them to tell each other at each step. Before you even touch the building, you have to present. You have to tell us what you're going to do. So it wasn't like a secretive thing. You didn't keep from other groups your ideas. Everybody had good ideas, and everybody told each other their good ideas, and then they were all fair game. And it was like you were rooting for each other to do well, so that then you could see if their idea was good and maybe use it.

Laura's framing of the task helped here as well. With no aspect of assessment dependent on performance, students were free to explore and improve on ideas that they found interesting. The lack of competition, combined with the focus on experimentation within the design project, helped students to balance the engineering aspects of their design with inquiry into the factors affecting their design.

Reframing competition: Renee's classroom

> *Renee used the Composites module for the second time. Her experience the year before was quite positive, but she intended to make some changes to the design project as a result of what she saw. This case is particularly interesting because of how Renee uses assessment to limit competition, and because of her decision to essentially not tour the classroom while students worked on their designs.*

Background

At the time of the project, Renee was a veteran science teacher in an urban high school just outside Chicago. She used the Composites module in her accelerated sophomore chemistry/physics class. Renee had attended a week-long summer workshop about the Materials World Modules and had taught the Composites module once before.

The class was one of four accelerated chemistry/physics classes that Renee taught; it met during the last two periods of the day. The class contained 24 students; 8 were girls. Renee teaches the chemistry half of the class, and another teacher teaches the physics half. The class normally meets every day for a double period (93 minutes) and students alternate between physics one day and chemistry the next. Students worked in groups of three that they selected; each table in the class was shared by two groups. Students each kept an individual design log as part of their science notebook; the notebooks were turned in at the end of the unit for grading. The focal group for this case consisted of three girls, Ellen, Lori, and Carol.

The design project occurred only in the chemistry portion of the class, and took place over five days within the first month of the academic year. (While students would normally spend every other day in physics class, an accident had befallen the physics teacher, so students met for chemistry every day.)

Goals

Renee liked the open-ended nature of the module. She wanted her students to be able to pursue inquiry in a way that not only developed their investigation skills, but excited them about science as well.

> ...we're not really giving kids a chance to experience the excitement of science. We're boring them to death .... and, I think, my main goal is to look for... I'm really on a hunt for curriculum ideas that allow students to do science and... to go along in the inquiry continuum to do more open ended things... and the whole idea of design just fits right in.

Because she was using the module within the first month of school, she was also concerned about setting expectations for the year in terms of what students were expected to do and what kinds of assistance the teacher would provide. She wanted students to be more self-reliant, and come to her not for answers, but guidance.

Finally, Renee had tried the module the previous year, and while she fairly happy with its success, she was concerned that student designs were fairly haphazard and that there had been very little communication within the class. She intended to make some adjustments, primarily in the reframing of the design task, to try to address these issues.

Framing the task

Although Renee had only five days for the module, she was working with double periods, and so had substantially more class time than Laura. Renee used all of the staging activities, including an optional activity where students explored the effect of directional reinforcement by wrapping fiber-reinforced (strapping) tape around a foam beam in different ways. Renee spent about half of this time on the staging activities and half on the design project.

On the first day, students did the ice-reinforced toilet paper activity, the hunt for composite materials, and constructed the foam beams that they would use in an activity the following day. Renee also introduced a research project which students would work on outside of class: they were to research a particular composite material and its uses.

On the second day, students did an activity that used several different materials to explore the difference between strength and stiffness, and the foam composite activity, where students learn about the effect of bonding on composites.

The third day saw students engaged in the directional reinforcement activity, following which Renee introduced the design project. The previous year, Renee had presented the design project as a competitive engineering challenge, where each group was competing against other groups to design the best fishing pole. Students worked in groups, but each student made their own design. Renee had reinforced this by offering five extra credit points to the group that produced the best design of all her classes.

Encouraging competition in design projects can be risky, because the greater emphasis on performance may lead students to focus solely on performance, rather than investigating the factors that make the design work. In fact, the year before when Renee tried this approach, the result was a highly competitive atmosphere in which groups hid their work from each other and even from Renee, for fear of "industrial espionage."

Renee was aware of these issues; she valued the excitement that came from the competitive enterprise, but did not want that motivation to come at the expense of student collaboration. Her solution was to keep the extra credit points, as they did increase the interest level of many, although not all, students in the class. In addition, she offered two extra credit points to everyone in the class that produced the winning design. She explained the purpose of these points to her students, encouraging them to work together as a class, while remaining competitive with the other three classes that she was teaching. (One reason that the extra credit was intended to motivate students was that the main rubric, shown in Appendix A, did not place value on design performance at all.) She also explained her reasoning in an interview following the module.

> ...the (extra) credit part was because last year, though it was a lot of fun, it really was too competitive... I worry about the girls... and it just seemed that... they were missing the opportunity to learn from other groups and since I don't have all the answers, I don't want them to learn from me and nor, can they really because I'm not that... this is not something I've been teaching for twenty years. ...nor should this be something that they get from me. It's just more realistic to get it from other people... it's the way you function if you were working and that didn't happen last year, so that's why I decided to treat each class as a team... as a company. And you have the different teams within the company... and... encourage them to share and not hide things.

Students were also instructed to vary one thing in their set of designs, much as Laura's class had done. This decision was also in response to how Renee had perceived the design project went the year before.

> I didn't have the straws just vary in one variable... I had each person in the design team come up with a design. So, they tested these really three very different designs, and afterwards I realized that they couldn't attribute... a good strength or flexibility or a bad

> one... to any particular material because it was so... it was .. it wasn't a controlled experiment. So, the prototypes much more got along the line of a controlled experiment where they were just changing one thing for the most part.

Students began exploring design ideas towards the end of day three; although they did not yet have a chance to bring materials in, they were able to explore some of the materials from earlier activities. For example, the materials used in the strength and stiffness activity — plastic rods, wood skewers, and string — were materials that were compatible with the fishing pole design.

Day four was the primary building and testing day. Students brought in building materials (many had visited an art supply store Renee has recommended the day before) and built and tested their designs. Since two groups shared a lab table, students were able to easily observe what at least one other group was doing. Students also frequently left their lab table and went to see what other groups were doing, borrow materials, or ask Renee a question. Students measured the performance of their design via a formula that valued strength, flexibility, and weight. (Renee led a discussion where students generated these three criteria, but the specific means of testing these criteria came from the written materials.) Designs had to flex at least 2 cm when placed under a 10N load. If designs passed this test, their performance ratio was calculated by dividing the maximum load the design hold without breaking by the mass of the design.

As students tested their designs and evaluated their results, Renee encouraged them to write on the board the factors that improved or didn't improve their design. This was a means for sharing among the groups good and bad design ideas. Originally, Renee had intended to have groups make presentations of their results, but she had found in an earlier class this day that this approach wasn't effective because students couldn't always hear what other students were saying, and this early in the year, she felt that students didn't understand what giving a presentation entailed.

> I think this would lend itself well to a presentation. Yet, they had it so early in the year, we hadn't taught them about how to do presentations, and to just get them up there and say, "Present" , that's not the best way...

Another problem with presentations is that there was no permanent record of these design ideas. Using the board was her response to these problems.

On the final day, students had half the period (the other half was devoted to the return of the physics teacher) to redesign and test their fishing poles, after which they wrote their results, conclusions, and their reflections on the unit in their journals.

Touring and coaching strategies

Renee took a more hands-off approach to touring than Laura or David. Rather than continually moving among groups and initiating interactions, she monitored groups primarily to track progress, and required students to initiate conversation with her on substantive issues. One of her concerns was that students would rely too much on her for answers to their questions, instead of trying to solve the questions themselves. She felt this is was particularly important since it was only September, and students were still learning how they would interact with her. Renee explained her strategy this way:

> I find that with these kids at this time of the year, if I start talking with them, they get into the... they usually have been very dependent on teacher... much of their success is because they've been... in front of the teacher all the time. And, I find that if I remove myself a little bit from those interactions, they function more independently. It's so easy for them to just ask teacher the question... and I could keep saying, Oh, you need to figure that out... which I do... but, I find just removing myself and observing forces the kids to... figure it out on their own. So, part of it is creating a structure where they have to do that ... they can't fall back on their traditional means.

When students did initiate interactions with Renee, she tried to avoid making comments about their designs, because she was aware of the impact that her authority would have. Instead, she took more of a project management role, where she directed students to resources that could help them answer questions that they had. These resources included materials sources such as a local hobby and craft store and information resources such as the board where students shared the results of their design ideas.

She reminded students that she was learning too, and that to find answers to their questions, they would need to test their designs. This approach included designs that she did not think would succeed; she felt it was more important for students to learn that for themselves than to be told.

In this exchange, Renee finds a dispute within the group. Ellen wants to build a design that uses modeling clay packed inside the straw to provide better strength and flexibility. Both Lori and Carol believe that this idea will be a complete disaster, but have not been able to convince Ellen to abandon it. Finally, Lori and Carol decide that the best way to convince Ellen is going to be to help her build the clay design, so that they can test it and let the results speak for themselves. The two skeptics have just begun to help Ellen when Renee arrives to check on the group's progress.

TEACHER	Is this your second prototype?
ELLEN	They don't have any faith in my clay.
LORI	She (ELLEN) thinks that clay will work, so that's what we're testing. I have a feeling that clay isn't really going to do anything.
CAROL	It doesn't come back.

TEACHER	How come you've diverged so much from your original design?
ELLEN	We haven't. This is instead of wire.
LORI	We're replacing the clay with the wire and the rest is going to be the same.
TEACHER	Ok.
LORI	So we only made one variable.
TEACHER	Ok. So are you going to let the clay dry?
ELLEN	No. This is -
LORI	It doesn't dry. (Pause. TEACHER is looking at design. She smiles skeptically.)
LORI	See? Look at her face, Ellen! It's not going to work.
TEACHER	No, no, no! My face is fine. (Places hand on ELLEN’s shoulder.) I'm not going to…
LORI	I don't think it's going to work.
ELLEN	I don't care what her face says. (ELLEN never looked up from her work building the straw to see TEACHER’s face.)
LORI	She won't listen to us.
TEACHER	Well, it's worth a try. You have one more prototype.
LORI	It's not going to work....
TEACHER	(Starts to leave, and then returns.) Why don't you guys (LORI and CAROL) try something else?

This exchange illustrates Renee’s concern about students relying on her rather than working things out themselves. Despite her intentions, Renee’s nonverbal behavior communicated skepticism about the design idea. Lori jumped on the nonverbal cue and Renee’s status as additional support for her claim that the design idea wouldn’t work. Renee wants students to resolve these kinds of questions experimentally, and tries to downplay her reaction, encouraging the group to test the design and reminding Lori and Carol that, even if they don’t like this design, they will be able to try another. Pushing students to resolve their design decisions experimentally was a common aspect of Renee’s guidance.

Discussion

Students in Renee’s class displayed a more linear approach to experimentation, in effect engaging in a series of redesigns, rather than planning to build a series of designs up front, as students in Laura’s class did. For example, the focus group in this class built three designs over the course of the initial design building day. These designs corresponded to the three prototype that Renee asked them to build, and the designs did vary across a particular dimension: the students tried using different materials on the inside of the straw for reinforcement. However, the decisions about what materials to use were made iteratively, as the group tested and reflected on the performance of the successive designs.

Such an approach is a natural extension of design, and students in fact frequently engage in informal testing or rapid iteration during a single design phase. However, a consequence of this approach, which is often data-driven, is that the larger goal of generating valid evidence for one's design explanation is lost. In the case of the focus group, they realized after they had finished building and testing their first set of designs that they did not have a well-defined variable that cut across their designs. The group had to come in early the next day to build and retest three designs that incorporated the materials they had used the previous day — fiber optic cable, wood, and plastic rods — but in a comparative way.

Students spontaneously applied ideas and principles from the staging activities. One aspect of this application lay in the use of materials from earlier activities in their design. Students had learned about the strength and stiffness of different materials, and these materials could be incorporated directly into the design project. Students also applied ideas such as the principles of directional reinforcement. For example, the focus group discussed using reinforced tape in their design because it would stiffen the design longitudinally. (They incorporated this into one design, but ultimately decided that the additional mass the tape added to the straw outweighed the benefit of the added stiffness.)

Renee's approach to balancing competitive design goals with investigation produced a class climate that differed markedly from the previous year. While some groups wanted to win the contest, competition was not the driving factor. The focus group, for example, was more concerned with exploring their own ideas than they were with winning the contest. Here, Ellen describes what she thought was important to them about the project.

ELLEN Well, we didn't really feel that it was that important to make it the best one in the whole... section or grade level or whatever. But we were concerned, we thought that we just had a really good idea, on Friday, we're like, yeah, the fiber optic and wood are really going to work. So we thought that was the best we could do. So at the time we were thinking, yeah, we were concerned and we thought that was the best that we could do.

One reason the competitive aspect of the project did not take over the class as it had the previous year was the supports Renee provided to encourage the broad dissemination of ideas. By offering extra credit to the entire class, she encouraged students to share materials and ideas. This was evident in the nature of the class, where students moved freely among groups, often borrowing materials or talking about their designs. The use of the board as a clearinghouse for design ideas also served to make designs public knowledge. As a result, the focus group was surrounded with materials and ideas, and considered far more design possibilities than did the group in Laura's class.

Student-centered design: David's classroom

> *David was using the Concrete module for the first time. This case provides an interesting contrast to the two cases of the Composites module, and allows us to explore how a different written curriculum, based on the same premise of inquiry through design, may afford different aspects of student inquiry. David's framing of the task is also interesting because he gave his students more freedom to design their own material and design their own assessment.*

Background

At the time of the project, David was an experienced chemistry and biology teacher at a suburban high school near Chicago. He used the Concrete module in his regular level chemistry class. David had collaborated with Northwestern education researchers before, but only in his biology classes. This was his first experience using a Materials World Module.

The class was a mix of sophomores and juniors, and met during first period. Class periods were 55 minutes. Students worked in rotating pairs: David created new pairings of students for each new activity during the module. This case focused on following four of the ten pairs over the course of their design project.

The module took place over a month in the fall, although class days that were devoted to the module were distributed over this time. This was because concrete, the subject of the module, takes several days to cure, so students would make samples, work on other chemistry materials for a few days, and then return to the module once the concrete had hardened. The students spent five days on the design project and did not do a redesign.

Goals

David viewed the project as a chance for students to experience what he called *inventive thinking*. Inventive thinking refers to problem solving in open-ended environments, where creativity comes into play. This kind of task allows students to connect their scientific understanding to real world problems.

> ...the primary goal, I think... was about the nature of science. To... do science to get an experience, having to solve problems in an orderly fashion. You know... try to use scientific thinking to solve problems. And, I don't know if it's a separate goal or part of that, but, also the inventive thinking... thinking creatively to solve problems is kind of an offshoot of that.
>
> ...I think that we don't do enough inventive thinking, you know, where there's real opportunity for kids who are creative thinkers to apply what they're doing in the content area to a real world problem. So, that was... the reason I wanted to do this.

David was also concerned about the complexity of the design project. He saw that students would need to make many decisions over the course of the project, and, since he had never taught this module before, he wasn't sure that students would be able to address those decisions within the timespan of the project. Here, he describes his concern in hindsight.

> I just thought it was overwhelming that they had to come up with a concrete formulation, including reinforcements. They had to make the mold. They had to make it... they had to come up with a testing procedure from scratch that made sense... you know, that was quantifiable. They had to consider cost and, uh ... you know, whether this was going to be too heavy or too costly or whatever, to work for the purpose they designed it for. I mean it just seemed like there was an overwhelming number of sub-problems ... and if I had read ... I mean ...when we first started this... I was shaking my head... we're going to be doing this for eight months. There is no way in hell anybody's going to finish this by the end of the week.

David's concern about student's ability to address these design decisions meant that one goal was simply seeing students make it through the design project.

Framing the task

The Concrete module consists of five staging activities followed by a design project. (Two optional staging activities are included in an appendix of the teacher's edition.) Because several of the activities involve pouring concrete and waiting for it to set, this module is often used interspersed with other curricular activities; this was the approach that David took. The staging activities, design project, and redesign are expected to take around two weeks of class time.

David used all five of the staging activities, which took about a week of class time, but two weeks of real time because of the delay while students' concrete samples set. In addition to a concrete hunt activity where students searched for examples of concrete use in the world around them, students built samples of cement and concrete and explored the properties of concrete made from different ratios of cement powder, water, fine aggregate (sand), and coarse aggregate (pebbles). They tested the samples for strength and brittleness, and decided as a class which ratios produced the best results. Students also built a set of reinforced concrete samples, to explore the effect of different reinforcing materials on concrete's properties of strength and brittleness.

The Concrete module, like all Materials World Modules, actually has two distinct design projects which the students can do. One of these projects is more teacher-directed; it presents students with an existing challenge, and suggests to the teacher ways for students to evaluate their design. (The fishing pole project that Laura and Renee used is an example of the teacher-directed design project in the Composites module.)

The second project is more student-directed; in this project, students are challenged to come up with their own application for the material they are studying, and define for themselves how they will evaluate the success of their design. David chose to have his students do the student-directed project. While he was concerned that students might have trouble making the many decisions such a project requires, he felt that the project offered his students a greater opportunity to engage in inventive thinking than did the teacher-directed project, which challenged students to design concrete roofing tiles to meet a specified set of criteria.

David presented the project to his students as both simple and complex. He explicitly connected the previous work students had done exploring various concrete mix ratios. To help make the connection even more apparent, he had students document their results from the earlier test on large sheets of butcher block paper, which were posted in the back of the room where students could easily reference them. Here, David introduces the project to his class.

TEACHER So the idea of posting these things up here is that you're going to use those - this information, this data - as a reference and we certainly have a lot of different kinds of things that were tried. Ok. You can look around for a combination that you think would work for you in doing this next step. This is the design project.

I have assigned you a new partner and the reason for that is that if you get somebody who has some other experiences and the two of you get together, now you've had the combined... you have a large pool of combined experience working with the cement. You might have some better ideas than if we kept you with your same groups.

The purpose of this project - this is very open ended, ok - this is really what we've been working up to. I think this is going to be really exciting. This is an opportunity for you to think inventively. I think it's something we don't do enough of, especially in the science department. We do a lot of problem solving, and you do some, a lot of emphasis on experiments, but a lot of what goes on out there in the real world, in real jobs, is thinking inventively. You've got to come up with some new ideas and find some ways to test it.

So this project, this design project, is very complicated but the assignment is very simple. It's to come up with an idea for a product made out of concrete, and make it and test it. That's it. Now, you've got a lot of problems... it's complicated because "A" you have to come up with an idea that's manageable, something that you can handle doing. You've got to come up with a way to make the mold, right? And you know how many difficulties we had with those wooden molds as it was. I'll help with that a little bit. You've got to come up with a way to test it, ok? How can you test it to see if it's going to work? You can use some of the same tests that we did, but you don't have to limit it to that.

Students were given three days to brainstorm and propose their designs, build their molds, and pour their concrete, which then had time to set over the weekend. On the final day of the project, a Monday, students tested their designs, using tests that they devised, and then worked on their design logs, which were due at the end of the week. David encouraged students to keep track of everything they could in their design logs, because an important scientific skill is "careful record keeping." These logs, students' written records of the design project, were the "product" that would be assessed.

David's approach to assessment was also very student-directed; he believed that students would be better able to monitor their own progress if they generated the assessment criteria themselves. Towards the end of the second day of the design project, after students had had a chance to think about the project and what they would need to do to complete it, David devoted the last fifteen minutes of class to a discussion of assessment. In this discussion, two students served as recorders and wrote on the board the different criteria that students proposed for how they should be assessed. In effect, students built their own grading criteria. David let students generate their own criteria, limiting his contributions to suggestions for combining different categories and asking clarifying questions about student ideas. By the end of class, the students had converged on a list of eight categories, which David modified to get the five categories that were used for the actual assessment (see Appendix A).

> I think whenever you have a long term project like this... we want to encourage them to be checking up on themselves as they're going along and they need to know what their product has to be... what we're expecting of them. You know, it's really just a complicated... well, not complicated... a detailed purpose. And, if they don't have a criteria... an evaluation criteria that's reasonably specific, their products aren't likely to be as good, OK? So, I think that by having the criteria established up front, either by the teacher doing it, or by the students doing it, or the editors doing it... then the kids will get... they get more out of the experience because they know where they're going... they know where they are expected to go in general.
>
> ...to have them write it... takes some time, but then that's even better... because they've decided what they... you know, want it to be.

Because of time, David decided not to do a redesign; including the staging activities, he had already devoted the better part of three weeks to this module. Instead, David used the lack of a redesign to motivate student experimentation; he encouraged students to make multiple prototypes, so as not to put all their eggs in one basket. That way, they could explore a few different solutions for their design in spite of the fact that they did not have a formal redesign phase.

Touring and coaching strategies

David's approach to touring and coaching was driven by his concern that students might be overwhelmed with design decisions, at both a practical level (how to construct a mold for the concrete) and a more scientific level (deciding what mixture of cement, water, and aggregate to use and why). Since students were not doing a redesign, he was also aware that they had just one opportunity to make their design work.

In his interactions with students, David took on the role of fellow designer, in that his attention was focused on helping groups identify and address design problems, rather than focusing on inquiry. He was particularly focused on helping groups figure out how they would make their molds for the objects, as some of the designs groups came up with — concrete bowling balls and running shoes, among others — presented serious construction challenges.

In addition to providing suggestions to help students with the building phase of the project, he also reminded students to use the results from previous experiments, which were displayed on large banners near the back of the room, to inform their choice of concrete formulations for their design. But the primary role David saw for himself was that of a troubleshooter.

> Initially I wanted to coach them to, uh, think broadly. To not get focused on the very first thing that popped into their heads... to actually brainstorm and try and, you know... I kept encouraging them to list ideas, and then consider variations or other ideas. And, then I also considered... I think it's an important role for me to be a trouble-shooter and go to a group whose got an idea and their thinking about it and asking some questions about it. Especially if I anticipate that, for example, how would you make a mold for this? And not discourage them by saying that, but just sort of warn them that, yeah, that's a really great idea, you know, to make a computer keyboard out of concrete, but... that has a lot of working parts and... how would you do that? How would you make a mold for... could you just make part of that? You know, just one key, would that work? You know, instead of having to build the whole... just try and keep them working towards a tangible focused project. I think I also gave them ideas for materials and what I know is available in the lab that they could use... just to kind of speed them along so they didn't get too... like if a group was worried about finding some kind of a material... we really need to have some steel in this and I'd say well, I've got a box of screws over there, you're welcome to use those. So, any materials that they might need that I knew was available I tried to make them aware that it was there and it wouldn't be a big deal.

Discussion

Students in David's class drew heavily from the evidence from earlier activities in their design projects. This was not surprising because not only had the students spent more time on the staging activities than students in Laura's and Renee's class, but the data that they had collected about the strength and brittleness of different concrete formulations was directly applicable to their design work; most groups included either strength or brittleness as criteria for the evaluation of their design, so the results of the earlier formulations were immediately relevant. Students were also able to make predictions about the effect of modifying existing formulations, based on what they had learned in earlier activities. Many groups used the best formulations from earlier activities as a starting point, and varied these formulations to try to improve on them.

Students' ability to balance engineering and scientific goals was less clear. On the one hand, the fact that each group was designing and building their own product (a set of pots here, tree ornaments over there) meant that could be no competition over who had the best design. On the other hand, the lack of a redesign reduced students' incentive to develop explanations for their designs, and David's particular touring focus on solving design problems left him little time to direct student inquiry. As a result, while students varied aspects of their design, they often varied several factors at once, which left their claims about design performance open to alternative explanations.

Cross-classroom analyses

Each of these teachers approached the design project in different ways, reflected in the manner in which they created opportunities for inquiry and supported student inquiry during the design task. These strategies also reflect some of the tradeoffs teachers face in balancing their own goals for the unit with the goals of inquiry and design.

Helping students connect design decisions to scientific principles

Inquiry contributes to design through the application of scientific understanding to design decisions. The staging activities in the modules provide one source of ideas and principles; the design process itself is another. Teachers varied in how much emphasis they placed on students learning from staging activities and design. Laura drastically cut the amount of time she spent on staging activities, in order to place more emphasis on learning from the design project itself. David, on the other hand, created the opportunity for students to apply what they learned by devoting over a week to staging activities that had direct relevance to the design project. But since there was no redesign in his class, students could only apply principles from the staging activities; there was no opportunity to apply what they learned from their designs.

Renee provided time for both staging activities and redesign. Although she provided less coaching during the project, her students were able to consider materials and ideas from earlier activities as well as ideas that emerged from the first set of designs.

Helping students generate evidence to reason about design decisions

One benefit of design projects is that since testing designs in an inherent part of the process, students generate lots of data. However, without a scientific approach to experimentation, the data students produce will not be amenable to comparative analysis. Students reason about design evidence both to improve their designs and to construct explanations for design performance. This was Laura's main focus, and she created motivation for students to pursue both of these goals: they improved their designs via redesign and explained their design rationale via class presentations and design logs. Combined with Laura's touring focus, that resulted in student experimentation that consistently held other aspects of design constant and let students develop explanations for a particular design variable.

Renee also provided opportunity for redesign and encouraged students to develop explanations through her expectations for their design journals. However, students in her class seemed more data-driven in their experimentation, and generated a series of prototypes iteratively rather than designing an experiment to test a particular design element. Renee's decision to avoid proactive coaching during the design task may have contributed to this more exploratory approach.

David's class had even less motivation for experimentation during the design phase. Earlier activities had produced highly relevant evidence that students could apply to their designs, while the lack of a redesign removed the incentive to produce data during the design phase. While students did reason about evidence produced during staging activities, their design variants seemed to focused on improving their design, and often conflated design factors. While David was aware of the potential benefit of including the redesign in terms of inquiry, his concerns about the complexity of the project and time drove him to focus on the engineering nature of the project.

Helping students manage design complexity

Design projects such as these offer a tradeoff between completely open-ended design problems and more structured challenges. Laura's enactment of the fishing pole project, where she provided substantial support during the design process and essentially constrained students' focus to a specific design factor (the variable), helped students to generate evidence to help them understand how that factor affected their designs. On the other hand, students were not able to explore the design space as broadly as students did in Renee's and David's classrooms, where students had more freedom. But open-ended design projects add a degree of complexity to student experimentation. Design possibilities are limitless, and as students explore a broader range of design ideas, it becomes more challenging to discriminate among multiple design factors.

Helping students balance engineering and scientific goals

Each teacher addressed the concern of an engineering goal bias by reducing competition in the classroom; each accomplished this in a different way. Laura maintained a consistent focus on experimentation and explanation, and required students to communicate their ideas to others. Renee used a different form of competition, that of the entire class competing against other classes, to encourage students to collaborate and share design ideas. David defused the entire competitive enterprise by allowing students to choose their own design projects, thus eliminating any basis of comparison that might lead to competition. Further, all three teachers used assessment measures which did not value performance at all. (While Renee offered extra credit based on performance, her primary rubric did not mention it.)

Summary

Design is a promising context for engaging students in inquiry, but several concerns must be addressed if students are to successfully take advantage of the opportunities for inquiry that design presents. Written curricula may help address some of these concerns, but instructional materials are only one part of the classroom enactment. We are exploring the role that the teacher plays in framing design projects to create opportunities for inquiry and supporting student inquiry during the design task. Our results suggest that both of these aspects of enactment are critical if students are to successfully address the challenges of doing inquiry through design.

Teachers themselves face design decisions as they choose between alternate strategies for supporting student inquiry; decisions that help shape the design of the classroom learning environment. Teachers must consider many constraints in the design of their practice, including time, the goals they have for their students, and the goals of the curricula they use. Many of the design decisions teacher make must balance tradeoffs among these goals. The cases presented here represent three teachers' decisions and the tradeoffs those decisions entailed.

Future work will continue to build on these cases, with the intent of producing a theoretical model of strategic teaching support for inquiry through design. Such a model will inform development and dissemination efforts of design-centered curricula like the Materials World Modules.

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Appendix A. Formal assessment measures

Laura's Composite module rubric.

Categories		Points
Team worked together smoothly	a. **S**hared ideas b. **C**omplemented others c. **O**ffered help and encouragement d. **R**ecommend changes nicely e. **E**xercise self-control	3 3 3 3 3
Experimental Design	Team chose a variable Team proposed a procedure to test variable	5 5
Prediction	Results discussed before poles were built Thorough explanation of reasons for ideas	5 5
Building	Clear steps written for procedure Team followed procedure	5 5
Testing	Testing carried out in reproducible manner Recorded data in data table Provided diagram of testing apparatus	5 5 5
Questioning	Guiding question written for each stage of research Predictions made about the question Predictions reviewed in light of research	5 5 5
Redesign	Redesign plans were based on first design A new variable was chosen	5 5
Conclusion	All predictions were reviewed Experimental evidence used in explanation of phenomena studied Design question addressed	5 5 5

Renee's Composite Module rubric

Categories		Points
General	Recorded unit notes, directions in lab book	1
Ice Composites	Predictions, data, and conclusions in lab book	1
Composite Hunt	Students received 0 points for finding 0-3 materials, 1 point for 4-7, and 2 points for finding more than 8.	2
Strength and Stiffness	Predictions and data in lab book Graphed results in grid Definitions and conclusions	1 1 1
Foam Composites	Data chart Graph of data	1 1
Geometric Reinforcement	Predictions, data, and conclusions in lab book	1
Design Project	Initial Design: Procedure Data Conclusions Redesign: Procedure Data Conclusions	 1 1 3 1 1 3
Learning Log	Described five things they learned from doing the project. Students received one point for each thing they learned.	5

David's student-generated assessment categories

Category	Points
Each group will demonstrate cooperative problem solving behavior during the course of the project	5
Each group will demonstrate creative, flexible thinking by their actions during class periods, and as evidenced in writing in their Design Log.	5
Each group will have physical and written evidence (Design Log) illustrating the successful production of a new concrete product.	5
Each group will demonstrate problem solving skills through evidence of: consideration of various designs, varying formulations and reinforcements, and carefully planned testing procedures.	5
Each group will produce a concrete product, and a complete Design Log that includes a quantitative data table.	5