Designing inquiry: Contexualizing teaching strategies in inquiry-based classrooms

Eric Baumgartner
Graduate School of Education
University of California at Berkeley
ebaum@socrates.berkeley.edu

Abstract

Design projects are rich contexts where students can apply scientific inquiry to develop and test explanations for their design's performance. However, sustaining inquiry within a design context poses unique challenges. Students often focus on improving their design at the expense of developing scientific explanations, even though such explanations could inform later designs. To support student inquiry within this context, many teachers adopt a facilitative role, making decisions that affect the framing of the activity and engaging in ongoing coaching and modeling interactions with students over the course of a design project. What is the nature of these teaching strategies? To what extent can these actions, rooted as they are in the specific context of enactment, serve as general lessons for other teachers facing similar challenges?

This paper explores the diverse strategies three high school science teachers employed to motivate and sustain student inquiry within a design context. The analyses of these strategies draw on the specific aspects of each enactment to explain the intent and effect of individual teaching strategies. By characterizing the teacher as a designer of strategies for supporting inquiry, these instructional strategies are summarized in terms of design tradeoffs, based on the teacher's goals, previous experience with design projects, and knowledge of the classroom context, that may inform instructional practice in other inquiry-based environments.

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 and build 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

Paper presented at the Annual Conference of the American Educational Research Association, Montreal, Canada, April 22, 1999.

factors that influence their design. What they learn allows them to improve their design. Examples of design tasks include building a scale model of a bridge that supports as much weight as possible or constructing a roller derby car that travels down a ramp as fast as possible.

There are several reasons why design contexts may be well suited to inquiry. Design tasks are situated in real world problems, which allow 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, allowing students to apply what they learn to improve their designs (Perkins, 1986). Rarely do designs have one ideal solution, which allows students to pursue multiple design ideas. Students must also determine the means for evaluating the success of their design. The empirical tests that result generate data for students to use to reason about design performance. Students may draw on these results to reason about and iteratively improve their solution over time.

Obstacles to inquiry in design contexts

Situating inquiry in design contexts raises a number of challenges. Scientific inquiry can be difficult for students, and while design contexts can create opportunities for inquiry, they do not directly support student reasoning. Students who engage in inquiry often have trouble framing questions to explore, designing experiments to test their hypotheses, and using data to support their arguments (Klahr, Dunbar, & Fay, 1990; Kuhn, 1993; Scardamalia & Bereiter, 1992; Schauble, Glaser, Duschl, Schulze, & John, 1995).

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 impact 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.

A further challenge is that engineering design and scientific inquiry 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). This fixation is often exacerbated in competitive design situations, such as when all students in a class are striving to design the best bridge, or the fastest car.

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 creates promising opportunities, but does not provide specific support to help students engage in successful scientific inquiry. Successful design contexts must provide this support through either curricular or instructional means.

Supporting '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 pedagogical 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 that 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 opportunities for *iterative 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 just 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. Design cycles are structured as investigations, where students construct and test a series of design variants to determine the effect of specific design ideas on design 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.

How do teachers support student inquiry during design?

While we have tailored inquiry through design-based curricula to support student inquiry, written materials alone do not dictate classroom practice. Others have documented the use of inquiry-based materials in ways that do not support inquiry (Germann et al., 1996; Olson, 1981; Welch, 1981). We view students' engagement in inquiry as a process 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. Substantial portions of instructional practice — including coaching, scaffolding, and fading strategies — are left open to teachers' interpretation. For example, the Materials World Modules provide general suggestions about assessment, but no specific rubrics. Teachers must design their own means to set student expectations and evaluate student understanding.

How can we characterize the strategies teachers use to support inquiry through design? By observing teachers who engage their students in inquiry, we can begin to document specific teaching strategies for supporting inquiry (Baumgartner & Reiser, 1998). However, it is difficult to synthesize these individual cases into a broader model without a theoretical framework that takes into account the tradeoffs that teachers face in their classroom practice. Such a framework may prove 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.

We approach this question through the lens of design, characterizing instructional practice as a design task in itself. The act of teaching shares many traits with the engineering design tasks that we present to the students. Teaching is a complex activity and is driven by many distinct and often contradictory goals. Teachers must make decisions that involve tradeoffs among goals, such as the tension between covering curricular content and allowing students time to pursue their own investigations (Hammer, 1997). Teachers may employ varying instructional strategies to meet similar goals, taking into account the specific set of constraints and opportunities present in their classroom. As teachers modify their own practice over time, they must make sense of past instructional contexts in which they applied multiple strategies, making it difficult to disentangle the effects of one particular idea. Finally, teaching, like design, is an iterative practice, where teachers return to particular instructional units over the course of hours, days, or years. Teachers' awareness that they have ample opportunity to refine their practice may predispose them to think about their instruction as a process of iterative refinement. At the same time, the pressure to 'get it right the first time' creates a tension similar to that of design, where strategies that effectively optimize performance are in tension with strategies that promote reflection, inquiry, and learning.

The implications of thinking about teaching as design suggest that it is important to characterize the strategies that teachers use in a particular domain as design decisions that address specific design criteria. Some decisions are better than others; some decisions intentionally sacrifice one design goal in order to advance another.

Our goal for this paper is to present an overview of instructional strategies for inquiry through design within a teaching as design framework. Such a framework acknowledges that multiple strategies may achieve similar results, and teachers may adopt differing strategies in order to address varying design goals. The value of such a framework lies in providing information to teachers new to inquiry through design curricula that they can use to address the specific challenges of supporting inquiry in this context. Viewing teaching as a iterative design activity may also help us, as developers of curricular materials, design curricula that take into account the needs and expectations of teachers with varying degrees of experience.

Our analyses of teaching strategies focus on two specific aspects of classroom practice: how teachers frame the design task for their students, and how teachers provide support during the design task. The framing of the design task is important because it defines the nature of the task that students face. Depending on how the task is presented, different aspects of design that afford inquiry may be augmented or diminished. As an example, consider a design task that 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.

Teachers provide support for student inquiry throughout the course of 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, which occur while students are engaged in the design task, allow teachers to diagnose problems and 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 designs.

Towards a model of teaching strategies for inquiry through design

Teacher support for student inquiry is a critical aspect of the classroom enactment. Characterizing teaching strategies in a coherent framework allows researchers and educators to weigh the constraints, goals, and tradeoffs teachers make as they support student inquiry in different ways. Examining the classroom through the lens of design allows us to study how teachers provide opportunity for inquiry as well as how they help students to take advantage of these opportunities. This paper attempts to move towards a model for supporting student inquiry in design contexts by viewing teaching itself, and the strategies teachers use to support inquiry, as an iterative design task.

Method

This study is based on three teachers' enactment of inquiry through design curricula (see Table 1). In each case, the teacher used curricular units from the Materials World Modules projects]. The three teachers represented in these cases each succeeded in engaging students in inquiry in varying ways (Baumgartner & Reiser, 1998). Our intent here is to use specific examples from these classroom enactments to illustrate the nature of the design decisions that teachers make in their practice.

After providing some background information about the teachers and their classes, we will describe the different strategies these three teachers used to frame and support student inquiry. We focus particularly on the means used to address a fundamental tension in inquiry through design—balancing engineering goals of optimizing performance and scientific goals of understanding and explaining design behavior—and the strategies used to support student inquiry processes over the course of the design project.

We will also discuss how some of these strategies have evolved over multiple enactments of the curricula, and how the teachers themselves reflect on the redesign of their own instruction.

Table 1. Teacher experience using inquiry through design curricula.

Teacher	**Module**	**Prior Experience**
Laura	Composites	Laura was a fourth year teacher and was a co-developer of the Composites Module. She had taught the unit three times previously.
Renee	Composites	Renee had over fifteen years of teaching experience. She had attended a summer workshop about the Materials World Modules before using the Composites Module for the first time. This was her second use of the Composites Module.
David	Concrete	David had over twelve years of teaching experience, and had collaborated with Northwestern University researchers on other inquiry-based curricula. However, this was the first time he had used the Concrete Module.

Data sources. For each case, a researcher was present and observed in the class throughout the use of the module. 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.

Background

Each of the three teachers taught in a different high school in a different midwestern city. The specific contexts of each classroom, including the teachers' goals for the unit, are described below.

Laura. Laura was a fourth year chemistry teacher in a suburban Midwest high school. She used the Composites module in her regular level sophomore/junior chemistry class. As the module's co-author, Laura was very familiar with the unit and the goals of the development team. In addition, she had taught the unit twice within the past year. The module was used just before winter break as the culminating activity for a six-week unit on petroleum. Students spent six days on the project.

The observed class was an "early bird" class, which met prior to first period for fifty-five minutes. 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, 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.

Laura's goals for her students centered around the idea of working collaboratively and doing something on their own, without teacher direction. She emphasized this focus in an interview prior to the module.

> 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 it was also very challenging — "almost impossible" without a lot of help from the teacher. The tension between fostering student ownership in the project and providing support for student investigations was an important issue for Laura.

Renee. 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 taught the chemistry half of the class.) Renee had attended a week-long summer workshop about the Materials World Modules and had taught the Composites module once before.

The observed class, which met every day for a double period, contained twenty-four students; eight were girls. The design project took place over five days within the first month of the academic year. Students worked in self-selected groups of three. Each group member kept an individual design log as part of their science notebook; these notebooks were turned in at the end of the unit. The focal group for this case consisted of three girls, Ellen, Lori, and Carol.

Renee liked the open-ended design 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 so early in the school year, Renee was concerned about setting yearlong expectations, particularly in terms of student self-direction and her own role in the classroom. She wanted students to be more self-reliant, and come to her not for answers, but guidance. Finally, while Renee's experience with her first use of the module was fairly positive, she was concerned that student designs had been haphazard and that there had been very little communication or collaboration within the class. She intended to make some changes, primarily in reframing of the design task, to try to address these issues.

David. David was an experienced chemistry and biology teacher at a suburban Midwest high school. 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 unit based on inquiry through design.

The observed class was a mix of sophomores and juniors, and met during first period for fifty-five minutes. The module took place over a month in the fall, although class days that were devoted to the module were scattered over this time. (Since concrete, the subject of the module, can take several days to cure, students would make samples, work on other chemistry curriculum for a few days, and then return to the module once the concrete had hardened.) The students spent a total of five days on the design project and did not do a redesign. Students worked in rotating pairs: David created new pairings for each activity during the module. We focused on four of the ten pairs over the course of their design project.

David viewed the project as a chance for students to use a combination of scientific thinking and what he called "inventive thinking" to explore scientific 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.

Providing opportunities for inventive thinking meant giving students freedom to define their own design projects. At the same time, David was concerned about the complexity that comes with providing such opportunities. He saw that students would need to make an "overwhelming" number of decisions over the course of the project. Since he had not taught the module before, he wasn't sure that students would be able to address those decisions within the duration of the project. David described his initial concerns quite frankly, stating that there "was no way in hell anybody's going to finish this by the end of the week."

Managing the tension between engineering and inquiry goals

One important aspect of supporting student inquiry in design contexts is finding ways to manage the tension between engineering goals, which focus on producing a design that meets design constraints and optimizes performance, and scientific inquiry goals, which are more concerned with understanding how a particular design idea contributes to design performance. Here, we describe each teacher's approach to downplaying engineering goals in order to help students engage in scientific inquiry.

Laura

As a co-developer of the Composites module, Laura was well aware of the potential tensions between performance and inquiry goals. Laura addressed the tension between engineering and inquiry goals in several ways: focusing student attention on planning good investigations, using assessment measures that valued explanation, and requiring students to present their design ideas to the class.

Towards the end of the first day, Laura introduced the fishing pole design project, which is to design a prototype fishing pole, based on a drinking straw, using composite materials. She led a discussion in which the students generated the criteria they would use to evaluate their designs: strength, flexibility, and weight. As part of their designs, students were instructed to identify one variable that they would explore by building a set of five design variants. 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.”

Planning investigations were an important part of the redesign as well. Here, Laura encouraged students to take the best design from their first set of variants, and then explore the effect of another design idea. In this way, students were able to improve their designs while retaining a focus on scientific investigation. 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.

Laura’s assessment rubric (see Appendix A) also emphasized explanation instead of design performance. 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.

Laura also framed two presentations, one prior to building the first set of designs and one at the end of the redesign, as opportunities for students share their design ideas and explain how they thought the design ideas contributed to the fishing poles. The initial presentation was intended to make design ideas public, defusing any potential for competitiveness and secrecy among the groups. The final presentation was a chance for the students to explain how their design worked. Laura saw both of these presentations as opportunities for communication.

> 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.

Laura's goals for the unit, and her focus on the importance of experimental design, aligned well with those of the module development team – hardly a coincidence, since she participated in the development process. However, the strategies that she used are not the only means to support student inquiry. Instead, they reflected particular tradeoffs that Laura made. For example, emphasizing that students propose and then vary a specific design element limited the number of design ideas students considered. Laura also made the decision to devote the bulk of the limited time she had on the design project, rather than on the staging activities. The students' unwillingness to apply principles from the staging activities to their design may have been due in part to the limited time they spent on these activities.

Renee

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 the extra class time to run through all of the staging activities, spending substantially more time of them than did Laura. Renee spent about half of this time on the staging activities and half on the design project.

Renee had firsthand experience seeing how the competitive, design performance goals of the project could come to overwhelm the inquiry goals. The previous year, when she had run the project, students had waged 'industrial espionage' on each other, and got to great lengths to prevent anyone, including Renee, from learning about their design ideas. While Renee was thrilled with the degree of motivation and engagement that had resulted, she was wanted to create a more open, collaborative environment where students could work together to learn about their designs. Renee described her experience this way.

> ...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.

Renee planned to reduce competition in several ways, reframing the assessment rubric, encouraging each group to plan a comparative investigation, and requiring student presentations to share design ideas.

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. Renee had reinforced this by offering five extra credit points to the group that produced the best design of all her classes. Despite the fact that nothing in the twenty-five point assessment rubric (see Appendix A) valued design performance, the presence of the five point 'trophy' resulted in a highly competitive atmosphere in which groups hid their work from each other and even from Renee, for fear of "industrial espionage."

Renee's solution this year was to keep the extra credit points, as they did increase the interest level of many, although not all, students in the class. But in addition, she offered two extra credit points to everyone in the same class as the winning design. She explained that the purpose of these points was to encourage the students to work together as a class, while remaining competitive with the other three classes that she was teaching.

Renee also encouraged groups to plan comparative investigations similar to those in Laura's class, something that did not happen the year before. This decision was also in response to how Renee had perceived the design project went the year before, when she had allowed each student in a group to produce their own design.

> 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.

While this approach allowed more individual creativity and exploration, it didn't support student engagement in scientific inquiry, because designs were haphazard and students were not generating evidence that explained how a particular design idea contributed to overall performance. The redesigned project, which required each group to plan a comparative investigation as part of their first design cycle, provided this support.

Renee also planned to use student presentations to encourage the spread of design ideas within the class. Groups would present their initial results once they had tested their first designs. After she tried this with her morning class, however, she changed her mind. It became apparent to her that students needed the extra time to finish their designs, and many students needed more coaching to deliver successful class presentations. Renee reflected on this later.

> 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...

In place of presentations, Renee encouraged students to write successful and unsuccessful design ideas on the board as they learned about their designs. Although students were not required to provide explanations for why these design ideas performed as they did, the lists on the board did provide a mechanism for sharing design ideas.

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. 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 new focus on comparative investigations also helped students to generate evidence they could use to reason about the effects of specific design ideas. Finally, the use of the board as a clearinghouse for design ideas also served to make designs public knowledge.

David

David was using the Concrete module for the first time, and while managing performance and explanatory goals was not his main priority, he did frame the project in ways that helped to reduce this tension. By allowing students to define their own projects, and co-constructing an assessment rubric with the students, David was able to focus their efforts on learning more about their specific design ideas. At the same time, his decision not to include a redesign cycle encouraged students to try to combine comparative investigations with more exploratory efforts, which made it difficult for students to reason about the evidence they collected.

David addressed the competition aspect of the design project in a way slightly different from the other two teachers: he encouraged students to work on projects of their own design. Unlike the fishing pole project, where the design goals were effectively defined by the teacher, David challenged his students to come up with their own application for concrete, and define for themselves how they will evaluate the success of their design. 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. And since every student group was working on a different design challenge (e.g. one group tried to make concrete pots to boil water, while another made concrete bocce balls for lawn bowling), there was no opportunity for students to be competitive with one another.

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 the 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). David described the benefits he saw in having students become involved in the decision of how they would be graded.

> 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 ...[and] 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.

One tradeoff involved in having students define the grading criteria is that they may not arrive at categories that directly value the process of inquiry. David commented on how students sometimes choose categories that value good behavior (e.g. 'works well with others', 'makes it to class on time') instead of scientific understanding. From the perspective of performance versus inquiry goals, the student-designed assessment was neutral: neither goal was explicitly mentioned in any of the assessment categories.

Because of time constraints, 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.

However, the lack of a redesign reduced students' incentive to develop explanations for their designs. With only a single opportunity to meet their design criteria, the groups tended to produce one or two exploratory designs as well as a series of three to five designs that varied in a particular way. For several groups, the exploratory design outperformed the comparative ones, leading students to focus their attention on the best design, which was the one for which the students had no data to help them explain why the design did so well.

David's use of the student-directed design projects helped to reduce the focus on performance that results from competition between student groups. However, because students had only one change to make their design work, the lack of a redesign phase led students to focus on performance anyway. David was aware of this tradeoff, and planned to do a redesign the next time he ran the module. He felt that he had devoted as much time as he could afford to the module this year, and could not justify the extra time the redesign would take. However, he felt that having now run the module once, he would be able to find places where he could "cut corners" and essentially find time for the redesign by trimming time from some of the staging activities.

Summary

Each of the teachers described here used different strategies to encourage students to engage in inquiry and build explanations for how different design ideas affected design performance. While all teachers used assessment measures that intentionally avoided giving value to design performance, each found ways to reduce competition and a performance focus. Laura repeatedly emphasized the importance of designing comparative investigations, and used presentations to bring student design ideas into public view. Renee used extra credit as motivation to collaborate, and restructured the design cycle to require students to engage in comparative investigations. David downplayed competition from the beginning by having students work on individual design challenges.

Each teacher also faced specific tradeoffs as they chose to employ specific strategies. By focusing on comparative investigation so early, Laura limited her students' ability to explore a range of design ideas. Renee wanted to use presentations to help students share their ideas, but had to weigh that approach with her sense that, so early in the year, students had not been taught to make and listen to presentations in a productive way. And David's decision to allow students to design their own assessment meant that he was willing to live with whatever they decided, even if it did not directly target the goals he had for the unit.

Supporting student inquiry during design

In addition to framing design activities to support inquiry goals, teachers employ coaching and mentoring strategies during the design process itself that serve to support students as they plan, conduct, and reflect on their investigations. Much as framing strategies provide opportunity for inquiry, these strategies help to provide specific support for aspects of inquiry that students find challenging. Here, we describe the particular strategies teachers used while the design project was ongoing to help students structure their investigations in productive ways.

Laura: Teacher as Guide

Laura toured her classroom almost constantly. Unlike some teachers, who often return to their desk or to the front of the room between trips to visit students, 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. When she toured, Laura tended to initiate interactions with a group of students with questions that led to short discussions of a minute or two where students reported on their design and explained what they were planning to do. Laura usually had specific goals for these interactions that went beyond simply monitoring group progress. One main goal related to students' use of variables in their design.

Laura questioned the focus group about their variable several times while they were proposing and building their design. She wanted the students to have their experimental design in place before they began to build their designs. (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 had decided what to do but before they had begun to build their designs. Laura was visiting each group, soliciting their predictions for the performance of their designs.

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 goal for this touring cycle. The group's predictions are very general, and as she probes Laura realizes that the group hasn't completed their experimental design. 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 drew on work that students did in previous years to serve as models for the kind of comparative designs she expected from her students. She provided examples of experimental design for groups to use as analogies. On the second day, as students began to build their designs, she toured the class, carrying with her an example from the previous year.

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.

In addition to providing students with a model of good experimental design, the example also illustrated that student designs could incorporate more than just the variable.

Laura's approach to touring the classroom proved an effective strategy for supporting student inquiry. The frequency of her touring allowed Laura to continually evaluate student progress and provide specific coaching to help student construct successful investigations. As a result, students 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. 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.

Renee: Teacher as Project Manager

Renee took a more hands-off approach to touring than did 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 is asked to arbitrate 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 as additional support for her claim that the design idea wouldn't work. Renee wanted 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.

One consequence of Renee's hands off approach was that students were more free to engage in design exploration, which sometimes occurred at the expense of inquiry. For example, the observed group 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 did students in Laura's class. This group built three designs over the course of the initial design building day, and realized at the end of the day that they had varied several materials over the course of the three designs. This group remedied their error by coming in over the weekend to plan and conduct a comparative investigation, but much of their work from the day before could not be used to support their explanations for why their design worked.

David: Teacher as Troubleshooter

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 his students were not doing a redesign, he was also aware that they had only 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 proposed — 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.

The primary consequence of David's adopted role was that it did not allow him time to support student inquiry. The fact that every group was working on a different problem, combined with David's concern about whether his students would be able to make all the decisions needed to succeed with their designs, meant that David spent most of his time anticipating students' engineering problems, rather than focusing on scientific investigation.

David acknowledged this tradeoff, and agreed that in future years, he would be able to spend more time helping students investigate specific aspects of their designs.

> I mean when I do a lab that I'm familiar with, like .... dialysis tubing in biology or diffusion, or something... you know, I explain what to do, give them all the stuff and then I spend the whole period going around from group to group to group asking questions... answering questions... that facilitates their inquiry experience.
>
> And when something is open-ended as this concrete project, then you need a lot of coaching. And, see, I wasn't able to do that very well because I didn't know what was going on, there would be so many technical problems... that needed to be solved.

Summary

The varying strategies that the teachers employed reflected their particular goals that they held for the project, as well as reflecting how experience with the module contributed to each teacher's approach. Laura's touring strategies dovetailed well with her goal of encouraging students to conduct comparative investigations that informed their understanding of their designs. Renee took a more hands-off approach, in part because of her stated desire to set a precedent early in the year for students to view her as a resource, but not a source of answers. David, running the module for the first time, had his hands full anticipating student design problems; his touring focus had much more of a troubleshooting character.

Each teacher's approach also reflected specific tradeoffs. Laura's touring approach, which reinforced the view that students needed to define their variables early, limited the amount of design exploration that occurred. Renee's hands off approach fostered independence, but meant that she was willing to let students go far enough astray to figure out their errors on their own. Finally, David's attitude towards his first use of the module was centered on getting through it; he viewed strategies for inquiry support as something he would address next time, once he had this experience under his belt.

Teaching as iterative design

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 teachers make must balance tradeoffs among these goals. The cases presented here represent three teachers' decisions and the tradeoffs those decisions entailed.

The framework of viewing teaching as a designed activity lends itself well to characterizing the strategies presented here, where teachers employed a diverse range of strategies, or design ideas, to address a particular problem: balancing students' engineering goals with the need to engage students in inquiry. Each strategy reflects a set of design decisions that take into account the unique goals and constraints of a teacher's classroom context. Similarly, the strategies teachers used to support student engagement in inquiry during the project itself also reflected a particular set of tradeoffs, such as Renee's willingness to let students struggle with the very independence that she wanted them to have.

The strategies documented here also reflect the way in which teachers iteratively refine their practice over time. The case of Renee reveals one teacher's thinking about how to improve her practice to better achieve the goals she set for the curriculum. David's case portrays an experienced teacher who is very aware that he is struggling with a new curriculum, and who is confident that he will be able to shift the focus on his support strategies in later iterations of the module.

Future research will continue to develop the framework of teaching as design, and will consider how the goals and expectations teachers have for the adoption and use of innovative curricula like the Materials World Modules changes from their initial to later iterations. We are also interested in exploring the implications of the teaching as design model in terms of providing insight into how we can provide better support for teachers using our materials for the first time, perhaps by making explicit our own design decisions and the tradeoffs inherent in them.

Acknowledgments

This research was supported by a Spencer Foundation Dissertation Year Fellowship Grant to the first author and grant number ESI–9353833 to Northwestern University from the National Science Foundation, Dr. R. P. H. Chang, P.I. I am also grateful to the teachers and students at Glenbrook South High School, Evanston Township High School, and New Trier High School, where these observations were conducted. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of these institutions.

References

Ball, D., & Cohen, D. K. (1996). Reform by the book: What is—or might be—the role of curriculum materials in teacher learning and instructional reform? *Educational Researcher*, *25*(9), 6-8.

Baumgartner, E., & Reiser, B. J. (1997). Inquiry through Design: Situating and supporting inquiry through design projects in high school science classrooms. In Annual Meeting of the National Association for Research in Science Teaching (Ed.), *Oak Brook, Illinois* .

Baumgartner, E., & Reiser, B. J. (1998). Strategies for supporting student inquiry in design tasks. In Annual Meeting of the American Educational Research Association (Ed.), *San Diego, California* .

Bucciarelli, L. L. (1994). *Designing engineers*. Cambridge, MA: MIT Press.

Germann, P. J., Haskins, S., & Auls, S. (1996). Analysis of nine high school biology laboratory manuals: Promoting scientific inquiry. *Journal of Research in Science Teaching*, *33*(5), 475-500.

Hammer, D. (1997). Discovery learning and discovery teaching. *Cognition and Instruction*, *15*(4), 485-529.

Klahr, D., Dunbar, K., & Fay, A. L. (1990). Designing good experiments to test bad hypotheses. In J. Shrager & P. Langley (Eds.), *Computational models of scientific discovery and theory formation* (pp. 355-402). Palo Alto, CA: Morgan Kaufmann Publishers, Inc.

Kuhn, D. (1993). Science as argument: Implications for teaching and learning scientific thinking. *Science Education*, *77*, 319-338.

Linn, M. C., diSessa, A., Pea, R. D., & Songer, N. B. (1994). Can research on science learning and instruction inform standards for science education? *Journal of Research in Science Teaching*, *31*(3).

Olson, J. (1981). Teacher influence in the classroom: A context for understanding curriculum translation. *Instructional Science, 10*, 259-275.

Perkins, D. N. (1986). *Knowledge as design: Critical and creative thinking for teachers and learners*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Roth, W.-M. (1996). Art and artifact of children's designing: A situated cognition perspective. *Journal of the Learning Sciences*, *5*(2), 129-166.

Scardamalia, M., & Bereiter, C. (1992). Text-based and knowledge-based questioning by children. *Cognition and Instruction, 9*(3), 177-199.

Schauble, L., Glaser, R., Duschl, R. A., Schulze, S., & John, J. (1995). Students' understanding of the objectives and procedures of experimentation in the science classroom. *Journal of the Learning Sciences, 4*(2), 131-166.

Schauble, L., Klopfer, L. E., & Raghavan, K. (1991). Students' transition from an engineering model to a science model of experimentation. *Journal of Research in Science Teaching, 28*, 859-882.

Welch, W. (1981). Inquiry in school science. In N. Harms & R. Yager (Eds.), *What research says to the science teacher* (Vol. 3, pp. 53-72). Washington, DC: National Science Teachers Association.

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