Science by Design: How Teachers Support Scientific Inquiry Through Design Projects

A DISSERTATION

SUBMITTED TO THE GRADUATE SCHOOL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

for the degree

DOCTOR OF PHILOSOPHY

Field of Education and Social Policy — Learning Sciences

By

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EVANSTON, ILLINOIS

December 2000
ABSTRACT

Science by Design: How Teachers Support Scientific Inquiry Through Design Projects

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This dissertation explores the viability of engineering design contexts as venues for engaging students in scientific inquiry. Successful scientific inquiry is defined as generating productive research questions, planning comparative investigations, using evidence to reason about claims, and pursuing scientific explanations. I argue that design contexts offer several affordances for supporting student inquiry, but must be structured in certain ways to support inquiry successfully.

I describe a particular instructional approach called inquiry through design (ITD) that is intended to support student inquiry within design contexts. This approach guided the development of several curricular modules and was iteratively refined over the course of several curricular trials. It uses introductory staging activities to provide background information and a motivating design challenge to encourage students to build and test their own design ideas. Design investigations are structured as scientific experiments, where students build and test a series of design variants in order to isolate the effect of particular variables. Finally, iterative redesign allows students to apply what they have learned to improve their designs and provides additional opportunities for students to engage in inquiry practices.

To examine the impact and nature of ITD in classroom settings, I conducted three classroom studies. These studies, which detail student engagement in design and inquiry, provide evidence to show that students were able to engage successfully in challenging aspects of inquiry. The success of the inquiry through design approach is portrayed as a collaboration among the students, the teacher, and the instructional materials in specific classroom settings. I describe how the teacher shapes the classroom context and supports student inquiry during project work. I document and contextualize teachers’ strategic decisions in terms of their experience, goals, and expectations for the unit. The resulting detailed narrative cases of classroom practice inform teacher adoption of design projects.
This research contributes to ongoing discussions about the role of technological design in science education and presents design as a viable context for pursuing inquiry in project-based settings. It describes how elements of the ITD approach combine with teacher practice to scaffold successful student inquiry.
ACKNOWLEDGEMENTS

This work would not have been possible without the gracious consent of the many teachers who allowed me to visit their classrooms: Renee Dewald, Ken Doody, Despina Economou, Dave Goodspeed, Irene Hahn, Ron Harris, Preston Hayes, Charles Jones, Andy Merutka, Sue Peterson, Tammy Porter, Angelo Rivera, James Tefft, Ken Turner, Laura Walhof, and Brian Zimmerman. Although my dissertation focused on only three of these classrooms, my work has been greatly enriched by my opportunities to observe and work with these teachers and their students.

The Learning Sciences program at Northwestern is a curious thing. I have been fortunate to see the program grow from an ambitious effort to integrate the fields of psychology, education, and computer science to become a leading light in efforts to effect change in the classroom through cognitive research, innovative curriculum, and educational technology. The development of the program — and my own development as a graduate student — owe a great debt to Brian Reiser and Louis Gomez. Brian and Louis worked passionately to shape the LS program to reflect their own visions of how research in cognition and technology could contribute to educational change in real classrooms. Equally important, they empowered graduate students to play an active role in this process. I feel privileged to have participated in the growth of this community.

As my advisor, Brian’s contributions to my own development as a researcher have been significant. His guidance, patience, and relentless optimism have been wonderful examples of how apprenticeship models should work in academic settings. My experiences with other LS faculty also reflect the warmth, collegiality, and generosity of the program. Louis Gomez helped shape my interest in understanding teaching strategies and teaching inquiry. Jim Spillane guided my research in this direction and helped a former computer scientist come to terms with qualitative methodologies. Miriam Gamoran Sherin, who unfortunately came to Northwestern too late to be on my committee, generously took time to read early drafts of chapters.

I was also fortunate to work with a talented curriculum design team that helped develop the Materials World Modules and the inquiry through design approach that defines my work. Bob Chang and Dick Goodspeed provided guidance that helped turn some bright ideas
about design into reality. Ken Turner, Laura Walhof, and Matthew Hsu co-authored the Composites Module. Joe Biernacki and Laura Walhof co-authored the Concrete: An Infrastructure Module. Barbara Pellegrini’s boundless energy contributed to teacher excitement about MWM and opened doors for my research. And Bernadette Conley and Ruth Rozen helped to shepherd these projects from inception to publication.

My Spencer Dissertation Year Fellowship helped me learn to speak about my research in broader educational contexts and gave me confidence in the fundamental importance of what I was doing. Catherine Lacey’s picture should be in the dictionary under nurturing. She, along with Lisa Lattuca, Cyndi Bentel, and my fellow Fellows, helped to create a caring, supportive community that seemed to crystallize around Catherine from the very first meeting.

My experience as a graduate student was greatly enriched by those who shared the experience with me. Housemates Laura Dreisbach and Kelly Tremblay shared their experiences of graduate life in audiology and helped ease my transition from country mouse to city mouse. In the Learning Sciences program, the Reiserlings maintained a healthy environment for learning and research through equal helpings of encouragement, candy, comedy, hot water, hallway conversation, cynicism, and outright carnage. Bill Sandoval — the rest of my cohort — shared an office, war stories, and sports injuries. Brian Smith kept score. Iris Tabak shared her own brand of relentless optimism and showed us all what was possible if we’d actually work a little. Ben Loh shared his ideas and creativity, offered (with Diana Joseph) a place for me to stay while I was on the California Installment Plan, and was always willing to end the day by letting the games begin. Brian Smith kept score.

Some schools offer foreign exchange programs as part of the graduate experience. For a Reiser student, this means moving west and finishing writing on the California Installment Plan. I am grateful to friends and colleagues in the Bay Area who supported my efforts. Sherry Hsi, Jim Gray, and Chris Hoadley offered encouragement and served as vibrant examples that It Can Be Done. The WISE research group and the CILT leadership team have been supportive communities for research both old and new. Marcia Linn deserves special thanks for her insight, patience, and trust in me as I balanced time spent on the dissertation with my new responsibilities.
Finally, I doubt that I would have pursued postgraduate education had it not been for the positive examples of academic life set for me by my parents, James and Yolanda Baumgartner. They encouraged me from the start, and their love and friendship has sustained me during the long journey to the present day. Finally, I cannot begin to explain the importance of my wife, Laura Baumgartner, to my life and my work over the past six years. As collaborator, research subject, teacher, critic, and friend, she has demonstrated patience, trust, and love beyond all measure. I could not have done it without her.
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Chapter 1. Introduction

1.1 Inquiry in High School Science Classrooms

A major thrust of recent science reform efforts has been to engage students directly in scientific inquiry, which is argued to be a more authentic and effective learning context for scientific principles (Linn, 1992b; NRC, 1996). This sense-making approach to science allows students to plan investigations, gather evidence, and reflect on their findings as a means of exploring questions that they have about phenomena in the world.

Here inquiry is defined rather broadly as the process of doing science: generating questions and hypotheses for study, designing and implementing scientific investigations to pursue these questions, reflecting on the implications of the results of these investigations, and communicating these results to others (Germann, Haskins, & Auls, 1996). Such an approach is congruent with existing learning theories that emphasize that students learn best when they are actively engaged in authentic contexts where knowledge has utility (Brown, Collins, & Duguid, 1989; Honebein, Duffy, & Fishman, 1993; Lave & Wenger, 1991).

Inquiry is more than just a means to an end. Understanding inquiry and scientific argumentation is also important. Students who engage in inquiry are participating in an activity that is similar to actual scientific practice. As a result, students may better understand the nature of science, scientific inquiry, and what constitutes a valid scientific argument. They may analyze scientific arguments more closely instead of accepting them at face value (Edelson & O'Neill, 1994; Linn & Hsi, 2000; Roth & Bowen, 1993; Tabak et al., 1995; Welch, Klopfer, Aikenhead, & Robinson, 1981).

However, it is difficult to cultivate inquiry with textbooks and prewritten lab exercises that typically create the expectation of a single appropriate method and correct answer for each problem. The relative lack of inquiry-based activities, even in curricula claiming an inquiry approach, has been well documented (Germann et al., 1996; Pizzini, Shepardson, & Abell, 1991; Welch et al., 1981). Particularly lacking are opportunities for students to investigate questions of their own, develop their own methods to test hypotheses, or develop scientific argumentation skills such as linking scientific data to conclusions (Germann et al., 1996; Kuhn, 1993; Pizzini et al., 1991).
This lack of opportunity is evident in recent assessments of student scientific understanding. Student performance on the hands-on portion of the NAEP 1996 Science Assessment was poor, with only about a fourth of grade twelve students succeeding in these tasks. These tasks required students to “perform an investigation, make observations, evaluate experimental results, and apply problem-solving skills” — all aspects of scientific inquiry (O’Sullivan, Reese, & Mazzeo, 1997). Such poor results suggest that students need increased opportunities to engage in these kinds of inquiry activities.

Recently, researchers have designed curricula that attempt to incorporate inquiry-based activities into science classrooms in different ways. Many of these curricula emphasize giving students the freedom to ask their own questions or to pursue their own investigations (Barron et al., 1998; Jungck, 1991; Linn, 1992a; Roth & Bowen, 1993; Tabak et al., 1995). Projects which allow students to explore a question over time are often used to engage students in authentic scientific inquiry (Blumenfeld et al., 1991; Edelson, O’Neill, Gomez, & D’Amico, 1995; Ruopp, Gal, Drayton, & Pfister, 1993; Sandoval & Reiser, 1998; Songer, 1996; Vye et al., 1998). Students may define the question that they explore, and are often responsible for designing experiments or collecting observations to help answer the question under study. Such projects often explore familiar phenomena such as weather or local ecosystems, allowing students to draw on their prior experience and knowledge. Some examples of projects that reflect this approach include investigating whether the water from a local stream is safe to drink, or explaining how someone can balance on a moving skateboard (Marx et al., 1994).

As Krajcik et al. have noted, many of these efforts began in resource-rich classrooms, where teachers have substantial support in the classroom, including developers, researchers, and technology, to help make the project succeed (Krajcik et al., 1998). Fewer studies have examined the use of projects to support inquiry in more typical classroom settings. An important next step for the research community will be to examine how successful project-based approaches are in more realistic classroom settings.

1.2 The Challenge of Supporting Inquiry in the Classroom

Projects are often cited as promising contexts for inquiry, but what makes a project amenable to inquiry? What kinds of support are needed to make a project an effective
learning context? The move to develop and provide more projects and activities that foster inquiry is promising, but an important issue facing these more open-ended settings is what students will do with the additional responsibility of directing their own learning, particularly in typical classroom settings (Krajcik et al., 1998).

Both students and teachers face obstacles to successful inquiry. To paraphrase one researcher, open inquiry typically succeeds with some students of some teachers, some of the time (Hodson, 1988). A major challenge to enacting inquiry in the classroom is understanding how to create a motivating context for inquiry and how to provide ongoing support for both students and teachers (Edelson, 1999). Students may not be engaged by the project context, or may flounder when placed in an open inquiry setting. Teachers may lack experience supporting student-directed work. Classroom resources and instructional materials may not be sufficient to sustain ongoing student investigations. Further, all of these elements must work together to create a climate that supports student learning (Crawford, Krajcik, & Marx, 1999).

Here, I will describe key challenges students and teachers must face if students are to productively engage in scientific inquiry.

1.2.1 Obstacles to Student Engagement in Inquiry

Students differ dramatically in their individual success learning through inquiry. Students who come to the task with more sophisticated prior knowledge and with more effective hypothesis generation, experimentation, and data organization skills learn more from their experimentation (Klahr, Dunbar, & Fay, 1990; Schauble, Glaser, Raghavan, & Reiner, 1991a). Further, many students have trouble successfully engaging in various aspects of inquiry, including asking questions, planning investigations, reasoning using data, and pursuing explanatory goals.

*Asking questions.* An important element of student-directed inquiry is the ability to ask questions that may be investigated within the context of the classroom. Without appropriate questions to drive inquiry, students may have trouble defining goals and identifying investigations that will aid their understanding. For example, Barron et. al describe a model rocket activity in which the lack of a clear driving question limited students’ ability to learn from their designs (Barron et al., 1998).
Questions must be rich enough to sustain worthwhile investigation. For example, questions whose answers may be looked up in a book may be meaningful, but not suitable for inquiry. On the other hand, questions can be too complex. The realities of time and the resource constraints of the classroom may frustrate students who pursue such questions.

Students also need guidance to ask questions that are appropriate for a new domain. Research has shown that students ask better questions as they gain knowledge within a domain, but that without support, this process is slow and takes time (Scardamalia & Bereiter, 1992). While one solution to this might be to present students with didactic instruction before placing them in a position of asking questions, Krajcik et. al argue for approaches that give students more experience asking questions and observing how the investigations that proceed from these questions play out (Krajcik et al., 1998). More research is needed to explore ways to scaffold student questioning to lead to productive inquiry.

Planning experiments. Designing investigations to test hypotheses is a critical element of scientific inquiry; without it, students cannot generate comparative evidence to help them evaluate scientific ideas. However, research has shown that student heuristics for planning experiments to test hypotheses may not be effective.

For example, students often exhibit a tendency to search for confirming cases but not for disconfirming evidence (Klahr et al., 1990; Kuhn, 1993). Schauble has found that while student experimentation improved over time, students’ heuristics for investigation still favored their own theories and that children who applied more valid strategies learned more about the domain (Schauble, 1990). These findings suggest that students need guidance to help plan experiments that will generate valid evidence to inform their reasoning.

Reasoning using evidence. To make valid, informed decisions about scientific content, students must be able to reason effectively using scientific evidence. Such reasoning includes the ability to relate scientific data to specific claims and to reason systematically about scientific evidence.

Kuhn has noted that students face difficulty relating scientific data to scientific claims. She has shown that students frequently commit errors of false inclusion — attributing a result to a particular factor when other factors are also present — and calls on science educators to
address this lack by improving students’ exclusionary reasoning (Kuhn, 1993; Kuhn, Schauble, & Garcia-Mila, 1992). In a similar vein, Linn documented that students had trouble reasoning about scientific data in a systematic way (Linn, 1992a). This suggests that even in contexts where students successfully generate comparative data, they will need support to reason about the data effectively.

Pursuing explanatory goals. Successful engagement in scientific inquiry implies an explanatory goal, in which the decisions students make and the actions they take are informed by an interest in refining an explanation for scientific phenomena. Even if students have the ability to ask good questions, design effective investigations, and reason systematically using scientific data, students who lack an explanatory focus may choose not to engage in these tasks or may pursue goals that are not aligned with scientific investigation.

Particularly in problem-solving settings, students may adopt goals that focus on solving the problem, rather than understanding the solution (Barron et al., 1998; Schauble, Glaser, Duschl, Schulze, & John, 1995). For example, Schauble documents how students may become distracted with inappropriate aspects of a task, such as striving to achieve a particular empirical result rather than investigating a causal relationship (Schauble, Klopfer, & Raghavan, 1991b). Kuhn describes how children asked to figure out why a combination of chemicals turns a solution pink instead focus on trying to generate the pink color (Kuhn & Phelps, 1982). These results suggest that students need support to maintain an explanatory goal, particularly when alternative empirical goals are present.

While projects may provide a promising context for scientific inquiry, they also place a greater burden on students to direct their own learning and their own investigations. Asking questions, planning experiments, reasoning about evidence and pursuing explanatory goals are critical facets of scientific inquiry. The design of inquiry-based learning environments must provide structured opportunities and scaffolding for students to engage in these four challenging inquiry processes.

1.2.2 Obstacles to Teacher Support of Inquiry

Project-based inquiry places demands on teachers as well. Chief among these are demands for a change in the role the teacher plays in the project-based classroom (Blumenfeld et al.,
Inquiry-based teaching is a challenging change for many teachers, and simply providing inquiry-based curricular materials is no guarantee that student inquiry will result (Germann et al., 1996; Welch, 1981). Indeed, Crawford has raised the question of whether it is reasonable to even expect first-year teachers to successfully teach in an inquiry-rich setting (Crawford, 1999).

Part of the challenge facing inquiry teaching is to understand exactly what it is that teachers do to support inquiry in the classroom. A common misconception is that teachers somehow “fail” to implement inquiry — and other innovative instructional approaches — correctly, deviating in some fashion from the written curriculum. While there are certainly documented instances where inquiry-based materials have been used to poor effect (e.g. Olson, 1981), the world of the classroom is complex and instruction is dependent on more than written instructional materials. Repeated attempts to use curriculum to spark educational reform speak to the resiliency of classroom practice to external reforms (Cohen, 1988; Cuban, 1993; Kennedy, 1997).

What teachers do with innovative curricula is participate in the process of translating the material from a written curricula to one that is taught, or enacted, in the classroom (Cuban, 1993; Marx et al., 1994). The transformation of written materials to classroom practice changes the unit in way intended and unintended (Marx et al., 1994). This process of transformation is co-constructed among all participants in the classroom setting: students, teachers, and the instructional material (Ball & Cohen, 1996).

In fact, the translation from written curriculum to classroom practice may be thought of as an extension of innovation. A written curriculum is, at its heart, a didactic medium that cannot interact with teachers or students. Surely, 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 open to teachers’ interpretation.

From the point of view of approaches like inquiry that are grounded in constructivism and learning by doing, we might expect that teachers engage in many of the methods of supporting student learning, such as coaching, scaffolding, and fading (Collins, Brown, & Newman, 1989). But how do these approaches play out in the classroom of thirty students? What else do teachers do to support student inquiry, and how do they decide when to do it?
Understanding the role that teachers play in enactment, and the strategies that teacher employ to support student inquiry, is a critical step towards supporting inquiry in the classroom.

1.3 Situating Inquiry in Design Contexts

One promising approach to incorporating inquiry into high school science classrooms lies in situating authentic inquiry within an engineering design context (Barak & Raz, 2000; Cuthbert & Hoadley, 1998; Hmelo, Holton, & Kolodner, 2000; Kolodner, Crismond, Gray, Holbrook, & Puntembekar, 1998; Roth, 1996; Sadler, Coyle, & Schwartz, 2000).

1.3.1 Design in Science Education

Understanding and engaging in technological design is itself an important aspect of science education, as emphasized by the current National Science Standards (NRC, 1996). Technological design emphasizes the utility of knowledge and, in Perkins’ (1986) words, “knowledge as constructed by human inquiry rather than knowledge as ‘just there.’”

Engineering design tasks provide an opportunity to apply scientific understanding to produce a tangible artifact and help drive home the relevance of scientific principles to solve concrete problems. Since many design projects focus on familiar objects, students may be able to bring their existing knowledge and curiosity of how things in the world work to bear in their designs (Bucciarelli, 1994; Roth, 1996).

Engineering design and scientific investigation complement each other well. Design projects provide an application for scientific investigation, yet also create a need for further investigation to better understand how and why different designs perform. The United States space program in the 1960s is a prime example of this synergy, as the drive to reach the moon resulted in many scientific breakthroughs that were later applied to new design contexts away from NASA.

While a design context by itself may not directly address the problem of supporting students’ ability to engage in inquiry, design projects — particularly engineering design projects — do offer the potential for students to engage in inquiry.
1.3.2 Engineering Design Projects

Engineering design projects are a particular class of projects in which students propose, design, build and test an artifact to meet a specific need. Where project-based science places students in the role of practicing scientists, design projects ask students to engage in the practices of both scientists and engineers. Students working on design projects have built rockets, towers, bridges, and hot air balloons, among many other applications (Barak & Raz, 2000; Barron et al., 1998; Roth, 1996; Sadler et al., 2000).

Design projects rely on scientific understanding to inform student design. For example, in one of the design projects investigated in this dissertation, students are asked to design and build a prototype fishing pole using a variety of materials. To succeed, students must develop their scientific understanding of the properties of specific materials and apply this knowledge to design a solution that is strong, flexible, and light.

Using design contexts to engage students in scientific inquiry is appealing at several levels. Because of their interdisciplinary nature, engineering design problems can relate to a variety of scientific domains. Design problems’ applications to real world settings make them motivating to students. In the next section, I will explain how design offers the potential to support student inquiry.

1.4 The Potential of Design for Supporting Student Inquiry

I have presented design as a promising context in which students may pursue inquiry successfully. In this section, I will discuss the particular affordances design contexts offer to help students engage in four challenging aspects of doing inquiry: asking questions, planning investigations, reasoning using evidence, and pursuing explanatory goals.

Of course, simply affording inquiry does not guarantee that it will actually happen. Thus, many of the arguments presented here are couched in the conditional; they offer great promise, but only if certain conditions are met. In chapter 2, I will present an instructional approach called inquiry through design that builds on the potential of design to support inquiry.
Understanding how design affords inquiry begins with an understanding of the design cycle itself. Design is an iterative process that begins with an initial design goal and proceeds to build and test designs to meet that goal. The process consists of several steps.

- **Specify design goals.** The cycle begins with the specification of the design goals: what needs must the designed artifact meet? How can these goals be translated into specific criteria that can then be tested? Note that these specifications serve as a starting point for designers and may be amended in later iterations of the design.

- **Propose designs.** Next, designers propose design ideas that they think will meet the stated goals. Designers may explore one or more ideas at a time.

- **Build and test designs.** Proposed designs are then built and tested using methods established earlier. Typically this results in quantitative data reflecting the performance of each design.

- **Reflect on results.** Designers then evaluate design performance by comparing their empirical results, including any emergent design behavior, to their original goals and expectations for the design idea. Depending on the success of the design, designers may stop here, or they may iterate through the process again.

- **Iterative design.** Design frequently involves a series of iterations before designers feel that they have a suitable design that meets their needs. Iteration is informed by what designers have learned from prior results. Designers reconsider not only their design, but also the original problem, their design goals, and their evaluation methods.

The design cycle provides numerous opportunities for students to engage in challenging aspect of inquiry. Next, I will discuss how engagement in specific aspects of inquiry may be afforded by the design context.

### 1.4.1 How Design Affords Student Questioning

The first step in a design project is to define the design challenge in concrete terms so that designs may be evaluated against a set of criteria to determine how well they perform. Defining these criteria is also an exercise in problem posing, an important component of
inquiry. Before students can develop effective designs, they must decide what a good design should do.

This top level design question serves as a driving question for student investigation. A driving question frames student investigation around a key idea or topic, and supports the investigation of specific sub-questions by various student groups (Krajcik, Blumenfeld, Marx, & Soloway, 1999).

The iterative design cycle is driven by the investigation of these sub-questions, which seek to identify effective design ideas that relate the physical structure of a design to the functional properties that determine its performance. Effective design explanations address these questions, relating structure to function (Coyne, 1990). These questions serve to focus student investigation throughout the project and are suitable for scientific investigation.

For example, consider a design project we will investigate in detail in this dissertation: the fishing pole project. This project asks students to design an effective prototype of a fishing pole. Before students begin to build their designs, they must decide what a good fishing pole needs to do. This is the driving question for the project as a whole.

Important design properties of a fishing pole that students might identify include strength, so it won’t break; flexibility, to allow longer casts; and weight, so the fisher doesn’t tire over the course of the day. These three dimensions serve as functional properties that students target in their design. Students may need to investigate these properties to understand what they mean and how they may be tested. For example, students might not fully understand the difference between strength and stiffness.

It is important to note that even once these properties are defined, students must decide how to balance tradeoffs among them. For example, companies make fishing poles for a broad range of uses. A fishing pole used to catch swordfish or marlin at sea will look very different from a fishing pole used to catch trout in a mountain stream. Students must decide, for their purposes, which of these would be a more suitable design.

Once students have determined the requirements for their design, they turn to more specific design questions. What materials could they use to build a good fishing pole, and how would those materials contribute to the functional goals of their design? These questions are
suitable for inquiry because they may lead to specific investigations, where students build and test designs to better understand why their designs work.

For example, students may wonder what kinds of materials best reinforce the core of a fishing pole. They may design an investigation to compare several materials — wood, metal, and plastic — to see which works best. Here, the design question seeks to relate the use of specific materials to strength, a functional property of the fishing pole. Students might also explore the optimal amount of a single design material or compare different construction techniques using similar materials. Each of these investigations reflects a design question that connects structure to function.

1.4.2 How Design Affords Student Investigation

Design projects can also scaffold student investigation of these design questions. Using design iterations as contexts for experimentation provides students with a consistent, predictable form of investigation that is amenable to good experimental design. A design proposal is essentially a hypothesis: students predict a particular outcome based on how the design is made. Each design, or set of designs, that students build can then be viewed as an experiment to test the prediction (Petroski, 1982).

For example, students might predict that wrapping their fishing pole design with tape will improve its strength. Student test that prediction by building a design that includes the tape and comparing its performance to prior results. In addition, students might build a design without tape in order to compare the effect of the tape to a control, or build several designs that vary the kind of tape used or the amount of tape applied to generate comparative data that can be used to reason about the effect of different kinds of tape. Students use the evidence they produce to refine their explanation for how uses of tape contribute to the overall design.

From the perspective of inquiry, the advantage to design is that student investigations are based on existing activity: students are already building and testing designs as part of the design context. The main challenge is to structure this activity so that students view design investigations as scientific experiments, and plan these investigations to support reasoning about the effects of specific design ideas.
1.4.3 How Design Affords Student Reasoning

Another strength of the design context is the empirical data that results from design testing. The engineering design projects described here include the building and testing of physical artifacts. Testing a design generates evidence, both expected and unexpected, about a design’s performance. Expected data informs students’ main design questions, which relate structure to function. In the case of the fishing pole design, students testing fishing poles generate data about the strength, flexibility, and mass of their designs. They can use this evidence to reason about which designs work the best and which particular design elements contributed to this performance.

Unexpected evidence may include surprising or serendipitous findings that lead students to explore new ideas or even recast the driving design question. In testing their designs, students may discover unexpected properties or learn more about how the structure of their design contributes to performance. Iterative redesign gives students the opportunity to investigate these results. For example, many civil engineers are interested not only in how much stress large structures like bridges and buildings can undergo, but how and where these structures fail. Similarly, students testing their fishing pole designs for strength may be interested in learning when specific design materials fail. Ultimately, this knowledge may be more important than the overall strength of the design, because understanding the process of design failure better informs redesign by targeting specific design elements.

Students may also discover hitherto unknown properties of their designs. A well-known example of serendipitous design is the story of the invention of sticky notes. The engineer who invented the glue used in stickies was actually designing a new adhesive that performed terribly. The glue did not meet its original design goals, but it had an interesting, unexpected property: it would adhere lightly to many surfaces and could be removed easily without marring the surface. A few years later, another engineer with a different set of design goals — reusable bookmarks that stayed in place — revisited the glue and found a match between its properties and the functional demands of his design (Jones, 1994).

A final affordance of design for supporting student reasoning about evidence lies in the open-ended nature of design projects. Since design projects afford many different solutions, students can engage in unique investigations while sharing a common class goal. In this sense, students are pursuing individual research efforts related through a common driving
question. While one group of students explores the effect of different kinds of tape on their fishing pole, another group may be investigating the role of directional reinforcement, while a third group focuses on designing lightweight materials. Since all groups are investigating the same design question — *what makes a good fishing pole* — each group’s results may inform other groups’ designs. With design iteration, students have the opportunity to apply others’ results to their own design. From the standpoint of inquiry, this benefits students by providing them with more opportunities to reason about the relationship between design ideas and evidence that supports or refutes those ideas.

### 1.4.4 How Design Affords Explanatory Goals

While design offers a promising context for supporting inquiry, it presents unique challenges as well. A major concern is how well scientific goals of explanation relate to design goals. Design questions are well suited to investigation, as we have seen. From an inquiry perspective, effective design questions will explore the relationship between structure and function. However, the nature of student investigation in design contexts may not focus on these explanations.

Design is a particular kind of problem solving with its own epistemological agenda. Students engaging in inquiry within a design context are often pursuing goals that relate to design as well as inquiry. These goals, and the strategies used to attain them, may at times be in conflict (see Table 1.1).

<table>
<thead>
<tr>
<th>Design</th>
<th>Inquiry</th>
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<tbody>
<tr>
<td><strong>Strategies</strong></td>
<td>Screening, focus gambling. Rapid iteration often driven by empirical success.</td>
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</table>

Design projects have immediate functional goals that center on design performance. Success is assessed by testing a design to see if it meets a set of specified criteria. In contrast,
scientific inquiry focuses on refining explanations for phenomena in the world. In design contexts, this goal seeks to explain the relationship between the structure and the functional properties of the design (Coyne, 1990; Hmelo, Holton, & Gertzman, 1997). The success or failure of the design itself is less important than understanding the explanation behind the design’s performance.

Designers may adopt a different style of experimentation than scientists use in purely inquiry-based contexts. For example, they may rapidly screen several design possibilities, or use heuristics as they attempt to identify a particularly promising design idea (Bucciarelli, 1994). Students may also engage in what Bruner (1956) termed focus gambling, where they make several modifications to an existing design in hopes of achieving major performance gains (Schauble et al., 1991b). These approaches try to find promising combinations of design ideas quickly, and trade scientific rigor for exploratory breadth.

The empirical evidence that results from these strategies is often sufficient for optimizing design performance. These strategies may be appropriate towards the beginning of a scientific investigation, where students are seeking to identify a particularly promising design approach for further study (Beveridge, 1950). However, they are not appropriate for the comparative investigation best suited to inquiry. Focusing solely on improving design performance may lead students to pursue design solutions in a haphazard manner, resulting in superstitious design decisions, repetitive testing, and errors of false inclusion (Kuhn et al., 1992; Schauble et al., 1991b). A particular concern is that students will engage in the kind of investigation described by Klahr (1990) where design investigations serve primarily to confirm students’ existing design ideas instead of testing these ideas in a comparative way.

So while design contexts appear to shape questions that may lead to explanations, the epistemology of design itself may also lead students to focus on exploration, or performance, at the expense of understanding. An important concern facing the use of design contexts for inquiry is how the tension between these two goals may be resolved.

### 1.5 Summary of the Challenge

Providing contexts that support student-centered inquiry is an important goal in science education. Such contexts must support students as they engage in asking research
questions, planning scientific investigations, and reasoning from empirical evidence. Design projects are a promising context for inquiry because they offer authentic, motivating problems and the iterative design cycle provides an anchored framework for supporting specific inquiry processes. However, students who engage in inquiry in design contexts pursue both design and inquiry goals. A challenge facing educators is to create a design context that encourages students to develop their understanding of design factors, allows students room to creatively explore novel designs, and supports the process of engaging in scientific inquiry. Chapter 2 will present an instructional approach that leverages design’s affordances to meet this challenge.

1.6 Overview of Dissertation

This dissertation centers on exploring specific ways to incorporate inquiry into design contexts. The nature of inquiry within an engineering design context may differ from inquiry in other contexts. Design contexts themselves may need to be specifically tailored to support student inquiry. What does inquiry in such design contexts look like? How can we leverage the apparent affordances of design for inquiry while minimizing the tension inherent between design goals and inquiry goals? And finally, how do teachers incorporate new design contexts into classroom enactments in a way that builds upon the prior affordances of design?

Chapter 2 presents a model for structuring inquiry in design contexts called inquiry through design (ITD). This approach is intended to highlight design affordances while minimizing the tension between engineering and scientific goals. Here, I describe the components of inquiry through design and discuss how this approach is tailored to support student engagement in difficult aspects of inquiry.

Chapter 3 describes my main research questions and the methodological framework I use to investigate these questions. It describes the construction of three narrative cases of inquiry through design that corresponds to three different teachers’ use of inquiry through design curricula.

Chapter 4 presents condensed versions of these cases with the goals of providing enough detail to illuminate inquiry through design in practice and introducing the teachers and students whose experience in the classroom form the basis of the analyses that follow.
Chapter 5 describes and assesses the nature of student inquiry through design, drawing on the narrative cases to illustrate how students successfully engaged in aspects of inquiry and where students still faced difficulty. In light of these results, I will revisit the elements of inquiry through design and discuss how this approach contributed to student success in inquiry.

Chapter 6 turns from the students to focus on the role the teacher plays supporting inquiry through design. What decisions do teachers make to structure inquiry through design for students, and how do they support student inquiry during the design project? This chapter describes each teacher’s approach to supporting inquiry through design, and reviews teachers’ strategies across the three cases to identify general instructional approaches that are well suited to the design context.

Chapter 7 brings the student and teacher analyses together, and reviews what we have learned about student inquiry in design contexts and teachers’ strategies for supporting and extending inquiry through design. As I take a design perspective on inquiry through design as an instructional model, I will discuss the implications of these findings on the redesign of ITD and suggest ways that other research efforts may relate to this approach. Finally, I will close with a discussion of the implications of this research on the support of design and inquiry in science education and the role of the teacher is adapting and supporting innovative curricula.
Chapter 2. Inquiry Through Design: 
A Model for Situating Inquiry in Design Contexts

2.1 Inquiry Through Design

Design projects have the potential to allow students to engage in inquiry in meaningful ways by exploring scientific phenomena while participating in an authentic hands-on task. However, design projects by themselves, much like other project-based approaches, do not provide the necessary scaffolding and support that students need to overcome the particular challenges facing inquiry in open-ended settings. How can we leverage the strengths of the design context — motivating, ill-structured problems that require students to define their own goals, plan their own investigations, and reason with empirical data — while providing task-specific support to help students overcome obstacles to open-ended inquiry?

In this chapter I present one promising approach, termed inquiry through design (ITD), that addresses these concerns through a combination of curricular elements that I will describe. After outlining the genesis and development of the approach, I will briefly describe one curricular unit — called the Composites Module — that is based on inquiry through design. I will then use this unit to illustrate elements of inquiry through design and describe how these elements are intended to support student inquiry. Finally, I will raise some challenges facing the use of inquiry through design. The strengths of and challenges to ITD form themes that I will return to throughout the dissertation.

2.1.1 The Historical Context of Inquiry Through Design

A team of researchers, educators, and scientists collectively developed and refined the inquiry through design approach over the course of designing a series of curricular units in materials science (the Materials World Modules). Materials science is a relatively new field that investigates the relationships between the structure and properties of materials (Callister, 1994). A highly interdisciplinary field, aspects of materials science have begun to be integrated into high school science and technology courses (Blicblau, 1997).
The curricular development team included educational researchers, high school teachers, and materials science researchers. The development process for each ‘module’ consisted of a series of iterations. Activity and project ideas proposed by members of the team were developed and field-tested in one of more classrooms. The results of these early trials contributed to the redesign of the activities. Modules in final form were field tested at least once before they were made publicly available. Several modules went through two or three iterations before reaching final form.

The original purpose of the units was to teach high schools students about specific materials science topics, including composite materials, biodegradable materials, infrastructure materials, and others. The content learning goals targeted in each module varied with the subject matter, but in every case we intended the unit to support student inquiry. The inquiry through design approach evolved together with our curriculum development effort as we struggled to articulate general principles for creating activities and design projects that would encourage and support student inquiry. While the research reported in this dissertation explores the contribution of inquiry through design to student inquiry, it should also be noted that early stages of this research helped to contribute to the principles of inquiry through design (Baumgartner & Reiser, 1997).

The inquiry through design approach is based on the premise that students learn best when given the opportunity to engage in complex, authentic problems over an extended period of time. This approach is consistent with constructivist views of learning, where learners improve their understanding by continually interpreting and reconciling new experience with their existing knowledge (Brown et al., 1989; Honebein et al., 1993).

Prior work has documented the value of anchoring student activities in realistic, meaningful settings (Barron et al., 1998; Linn & Hsi, 2000). This work has led to a variety of science education efforts that engage students in inquiry-driven projects. In some cases, students explore questions that have been defined for them (Linn, Bell, & Hsi, 1999a; Sandoval & Reiser, 1998; Vye et al., 1998). In others, students participate in shaping questions that will guide their work (Blumenfeld et al., 1991; Gomez, Gordin, & Carlson, 1995).

Recently, researchers have begun to study the role of design projects as a means for learning science rather than as an end in itself (Barak & Raz, 2000; Cuthbert & Hoadley, 1998; Hmelo et al., 2000; Kolodner et al., 1998; Penner, Lehrer, & Schauble, 1998; Roth, 1996; Sadler et al.,
Inquiry through design, rather than focusing on helping students learn to design (Harel, 1991; Harel & Papert, 1991). The design process is used to facilitate student construction of knowledge, including difficult science concepts.

Inquiry through design differs from these efforts in that it explores the promise of design as a vehicle for learning to do inquiry. Science content understanding is not ignored; rather, it is presumed that successful inquiry will lead to better science understanding. ITD builds on past work in project-based settings and attempts to identify a core set of principles for structuring design so that it will support difficult aspects of student inquiry. Next, I will describe the core elements of inquiry through design and walk through the structure of the Composites Module to illustrate these elements in a curricular context.

2.1.2 Overview of Inquiry Through Design

Inquiry through design is an approach to learning environment design that seeks to leverage the affordances of the design context for inquiry. Although design projects afford several aspects of inquiry, they do not always require designers to engage in inquiry to produce a successful design. Inquiry through design emphasizes particular aspects of the underlying structure of engineering design projects in order to highlight the role of inquiry in the process, and provides specific support around these aspects in order to help students engage in inquiry. This support, shown in Figure 2.1, includes staging activities, authentic design challenges, design cycles structured as scientific investigations, and the opportunity for iterative redesign.

Before discussing each of these elements in depth, I will describe the Composites module to illustrate how these elements are translated into a curricular unit.
2.1.3 Example: The Composites Module

A development team of researchers, educators, and scientists has produced several curricular modules for high school science classrooms that draw on ITD principles to engage students in design projects. These modules are part of the Materials World Modules research project. Each module occupies one to two weeks of class time and consists of
several introductory staging activities followed by a design project. Two of these Materials World Modules — *Composite Materials* and *Concrete: An Infrastructure Material* — were used in the classroom studies of this dissertation.

The Composites module is intended to teach students about properties of composite materials (Hsu, Walhof, & Turner, 1996). Composites are ubiquitous in everyday life. Bicycle frames, tennis racquets, Gore-Tex™ raincoats, and plywood are but a few examples of composite materials. The premise behind composite materials is that by combining multiple materials, one can create a new material with more desirable properties than any single material could provide. For example, composite bicycle frames and tennis racquets can be as strong and stiff as steel, but much lighter.

<table>
<thead>
<tr>
<th>Activities</th>
<th>1. Testing Different Kinds of Ice</th>
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<tr>
<td></td>
<td>2. Hunting for Composite Materials</td>
</tr>
<tr>
<td></td>
<td>3. Exploring the Difference Between Strength and Stiffness</td>
</tr>
<tr>
<td></td>
<td>4. Testing a Foam Composite for Strength and Stiffness</td>
</tr>
<tr>
<td></td>
<td>5. Geometric Reinforcement (optional)</td>
</tr>
<tr>
<td>Design Projects (choose one)</td>
<td>1. Designing a fishing pole</td>
</tr>
<tr>
<td></td>
<td>2. Designing a new material</td>
</tr>
</tbody>
</table>

The written materials for the module include a spiral bound student guide, a larger wraparound teacher’s guide, and a set of black line masters (BLMs) for each activity. The module includes four core staging activities and one optional activity that provide students with an introduction to composite materials and two important physical properties of these materials: strength and stiffness. Each activity is a structured investigation and includes at least one reflective question that prompts students to think about the design implications of what they have learned.

Each activity follows a common format, designed to foster prediction, investigation, and reflection. An activity begins with an introduction, after which students are asked to write down a prediction explaining what they think will happen and why. Students are then
guided through an investigation, including a step-by-step procedure (if appropriate). They are encouraged to document their experimental results in their own lab book or on the BLMs. After the experiment, written questions prompt students to interpret their data and reflect on their findings. These reflective questions may ask students to compare their findings to their initial predictions or consider the design implications of what they learned. Finally, students are prompted to document any new questions that have emerged over the course of the activity.

**Activity 1: Testing Different Kinds of Ice.** This short demonstration activity asks students to predict which of two ice disks will be stronger: one made of water, or one made by combining water and toilet paper in a blender. Students discover that the composite disk is much stronger than the plain ice disk, even though toilet paper is not very strong. The implication is that composite materials are important because they can achieve better properties than plain materials.

**Activity 2: Hunting for Composite Materials.** Students then go home and hunt for several composite materials in their house and neighborhood. For each material, students are asked to explain the design goals of the material and speculate on why multiple constituent materials were used rather than a single material. Students then share and discuss their findings in class. This activity helps to refine students’ understanding of what a composite materials are and provides practice explaining the properties of a material in terms of its structure: an explanation pattern that will be used in the coming design project.

**Activity 3: Exploring the Difference Between Strength and Stiffness.** Groups of students are given a variety of materials — including wooden sticks, string, pipe cleaners, and plastic rods — and are asked to rank the strength and stiffness of each material. The materials are carefully selected to provide examples that include strong, flexible materials as well as weak, stiff ones. The purpose of the activity is to differentiate two properties, strength and stiffness, that are often viewed as one. Strength and stiffness are two of the more important properties for which composite materials are designed and are also two of the design properties in the upcoming fishing pole project.

**Activity 4: Testing a Foam Composite for Strength and Stiffness.** Students conduct an experiment using a series of foam composites to explore the effect of laminar reinforcement. The composites consist of a small rectangular beam of polystyrene and strips of construction
paper. A series of varying beams are produced by gluing a strip of paper to the top, the bottom, or both sides of the beam. The students then qualitatively or quantitatively measure the stiffness of each beam by bending them.

The activity has three main goals. First, it is designed to introduce students to the difference between compressive strength (resistance pushing) and tensile strength (resistance to pulling). Paper is strong in tension, so adding paper to the side of the beam that is in tension will improve the composite’s stiffness. Second, the activity is designed to introduce students to the importance of bonding composite materials together. One of the beams has paper on one side, but the paper is only glued at the ends, not the middle. Students can observe that when this design is bent, the unglued paper comes away from the beam and buckles; the design is no better than a plain foam beam. Finally, the activity models good experimental practice for students, providing them with an example of a comparative design investigation in which several design variants are built (the foam-and-paper beams) and students must reason about the results to evaluate the effect of the design idea (reinforcing the beams with paper).

Activity 5: Geometric Reinforcement (optional). Students reinforce foam beams with fiber-reinforced tape. The nature of the reinforcement is similar to the prior activity in that tape has good tensile strength and can improve design stiffness. However, the experiment asks students to vary the geometric orientation of the fibers in the tape to see which orientations contribute the most to design stiffness. The goal of the activity is for students to realize that the orientation of reinforcement, as well as the nature of the materials, can affect design properties. Here, unlike the previous activity, students plan their own investigations, experimenting with different geometric orientations on their own.

Design Project 1: Designing a Fishing Pole. This design project is presented to students as a written challenge.

Catch More, a fishing supply company, is holding a contest for the design of a new fishing pole. The winning fishing pole will be made of a composite material. Enter the contest and take up the design challenge!

Your group will be given a set of drinking straws to use as a base for your prototype design. With your group, you will design, construct, and test a set of prototype fishing
poles; after you evaluate your design and have it critiqued by others, you will have an opportunity to redesign your fishing pole based on what you learned from working on your design.

Students and teachers are encouraged to discuss important design properties of fishing poles and how they might test these properties. They also discuss how students might compare designs with varying properties. If one design is stronger, but another is more flexible, which is the better fishing pole? The curriculum suggests focusing on strength, stiffness, and mass, and provides a mathematical equation — the *design ratio* — for combining these properties into a single performance value.

The design project is structured like an investigation and the written materials provide prompts to help students engage in this process. To begin, the curriculum prompts students to propose a set of three to five prototype fishing poles that vary in only one way. Students read that this approach will help them to evaluate the effectiveness of the design.

Students are then asked to predict and explain how their prototypes will perform, and to develop a repeatable procedure for constructing and testing the prototypes. They record and interpret data from these tests, and then reflect on their original predictions. Students are encouraged to present their results to the class and to constructively critique other groups’ designs and design results.

After this main design cycle, students are given an opportunity to redesign their fishing pole. The redesign is also structured like an investigation and students again construct, build, and test a series of design variants. Finally, students are encouraged to reflect on what they have learned over the course of the design project.

*Design Project 2: Designing a New Material.* An alternative design project asks students to choose an object to design. Students then design that object out of composite materials. Students in Composites Module classrooms have chosen to design prototype bridges, roadways, carpets, and pole vaulting poles, among many other objects. This design project provides an investigative structure similar to the previous design project, prompting students to propose a set of design variants, make predictions, collect and interpret data, and engage in redesign. It adds to these elements the responsibility to identify a design
challenge, identify core design properties for that challenge, and figure out how to test for these properties.

### 2.2 Supporting Student Inquiry via Inquiry Through Design

In this section, I will describe in detail each of the four elements that comprise inquiry through design, using the Composites module to illustrate how particular pedagogical ideas translate to written curricula. I will also explain how these elements are intended to support four challenging aspects of student inquiry: asking questions, planning investigations, reasoning with data, and pursuing explanations.

#### 2.2.1 Staging Activities that Model Inquiry

Staging activities are shorter, more structured investigations that precede the design project. They share many traits with staging activities in other environments that use projects to help prepare students for more open-ended investigation (Barron et al., 1998; Edelson, 1999; Krajcik et al., 1999). In staging activities, students investigate specific properties and materials that relate to the design challenge and to the curricular learning goals. Staging activities serve two purposes: they provide a scientific and experiential foundation for student understanding of the principles and concepts that inform the design project, and they model the design investigation process that students will engage in during the design project.

To generate good questions that can lead to inquiry, students need to have knowledge about the subject domain (Scardamalia & Bereiter, 1992). Staging activities are intended to help students understand important design properties and gain experience with materials that they may use in the design project. For example, activities in the Composites module emphasize the difference between strength and stiffness, and students investigate important scientific ideas like the difference between tensile strength and compressive strength and the role of different kinds of reinforcement. Students also practice asking questions. The final step in each staging activity prompts students to brainstorm new questions that may serve as starting points for later investigation.

Staging activities also model the investigation process, engaging students in structured investigations that propose a set of design variants, test these designs, and use the empirical
results to reason about design ideas. Later, students will be asked to plan their own investigations to investigate their own design ideas. For example, the Testing a Foam Composite activity demonstrates how to design a set of prototypes to explore how a particular kind of laminar reinforcement contributes to strength and stiffness.

In addition to structured investigations, students need to become familiar with the nature of design explanations. Staging activities model design explanations that relate structure to function. This is important because the goal of the design project is to explain design performance. Understanding the nature of design explanations will help students to pursue that goal. For example, Hunting for Composite Materials introduces students to explanations that link the structure of composite materials to their function in the world. Good design explanations will link structure to functional design properties.

Finally, staging activities provide students with empirical results that can inform their later design. The materials that students use in Testing Materials for Strength and Stiffness can also be used to reinforce students’ fishing poles. The results of the Geometric Reinforcement activity can inform decisions about orienting reinforcing materials to maximize tensile strength. The lessons learned from these activities have direct bearing on the design project. The reflective questions that conclude each activity are intended to help students think about how these results will contribute to their designs.

2.2.2 Authentic Design Challenges that Afford Inquiry

The selection and framing of an appropriate design challenge is the cornerstone of inquiry through design. Effective design challenges must be authentic, relate to curricular learning goals, support a diversity of design approaches, and generate empirical evidence. The design tasks themselves are presented to students as written design challenges, although teachers may choose to present the challenge in other ways.

Design tasks in which students understand neither the purpose of the design nor the scientific principles by which design decisions are made may leave students unsure of what to do next and unable to generate or justify new design ideas. Effective design challenges should leverage students’ everyday experience to motivate participation and help students understand the goals of design. For example, many students are familiar with fishing and can explain what a fishing pole must do to function well. In classes where students are less
familiar with fishing poles, another design challenge may be more appropriate. For example, in one classroom, a teacher chose to have students build kite struts instead of fishing poles because he felt his students were more familiar with kite flying than fishing.

Design challenges must also relate to specific curricular learning goals and support design explanations that relate structure to function. Ideally, it is only through mastery of the unit’s learning goals that students can generate successful designs. However, many design tasks can be successfully addressed through perseverance or trial and error rather than insight. Inquiry through design projects must make the value of learning and applying specific content instrumental to the success of the design project. In the case of the fishing pole project, the criteria by which designs are judged — strength and stiffness — represent two of the most important properties of composite materials. Thus, student investigation is always centered on these key learning goals. Further, students’ design explanations must focus on explaining how the structure of their fishing poles relates to these two functional properties.

A third goal of good design settings is to require students to consider multiple design ideas that involve intricate tradeoffs among desired design factors. Good design challenges should be complex enough to support multiple investigations within a class of students and rich enough that students can continue to improve their designs over multiple design iterations. The fishing pole project, for example, forces students to deal with two common tradeoffs found in composite materials: strong materials are often stiff, and strong materials are often heavy. Students may choose to build designs that value one property more than another: light, flexible designs may do as well as heavy, strong ones. These tradeoffs make the process of comparing designs more complex and create room for alternative design ideas. Students have freedom to pursue different design solutions instead of converging on one ideal design.

A final feature of suitable design tasks is that they support empirical testing. One of the great strengths of design contexts is that they are capable of generating both qualitative and quantitative data that students can use to reason about their own designs. Any design task that intends to support student inquiry must allow students to construct empirical tests of their designs. In the case of the fishing pole project, students can build and test their designs fairly easily, using tests introduced in the staging activities to measure the strength and
stiffness of their designs. Students can also observe their designs while they are tested and gain insight into how specific design components contribute to overall performance: for example, by identifying the first material to break as their design begins to fail.

2.2.3 Design Cycles Structured as Investigations

Another important element of inquiry through design is the use of the design cycle to scaffold scientific investigation. This approach values explanatory goals and makes them explicit, while also giving students opportunity to pursue design goals. Although retaining performance goals raises the risk that students will fixate on them, this approach acknowledges such goals as intrinsic to any authentic design task, and attempts to create a framework in which students recognize and pursue both goals.

The processes of design and inquiry share a number of similarities, although the ultimate goals of each cycle differ (see Table 2.2). In this approach, the more concrete steps in the design process—propose, build, test and evaluate—serve as anchors for more abstract inquiry steps such as question, predict, experiment and reflect. With this approach, questions about the effect of design ideas become the main research questions that students explore.

**TABLE 2.2.** ALIGNING THE STEPS IN DESIGN AND INQUIRY CYCLES

<table>
<thead>
<tr>
<th>Design cycle</th>
<th>Inquiry cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Goal:</strong> A functional design</td>
<td><strong>Goal:</strong> An explanation</td>
</tr>
<tr>
<td>Choose a design idea to explore</td>
<td>Define a question to investigate</td>
</tr>
<tr>
<td>Propose a design or set of designs to test the design idea</td>
<td>Plan an investigation to explore the question</td>
</tr>
<tr>
<td>Predict results based on claims about design idea</td>
<td>Predict results based on initial explanation or hypothesis</td>
</tr>
<tr>
<td>Build and test designs</td>
<td>Conduct an experiment</td>
</tr>
<tr>
<td>Analyze empirical results</td>
<td>Analyze experimental data</td>
</tr>
<tr>
<td>Apply results to improve designs</td>
<td>Reflect on findings to inform original question</td>
</tr>
</tbody>
</table>
In inquiry through design projects, developing an explanation for design performance becomes an explicit goal of design investigations. In fact, inquiry through design views each design cycle — which begins with a claim or question about the effect of a particular design idea and leads to the construction and testing of one or more design variants to explore the idea — as a scientific investigation. Assessment recommendations in the teachers’ guide encourage the use of assessment measures that value investigation and explanation rather than assigning grades based on design performance.

Inquiry through design scaffolds design investigations by prompting students to vary only one design element at a time. Because all other design elements are held constant, students can focus on a single possible cause for change across a set of design variants.

This approach is consistent with the goal of developing explanations that use empirical evidence to relate structure to function. For example, a student in the fishing pole project might investigate how different kinds of tape reinforce the outside of the fishing pole. A careful investigation will enable the student to relate the use of these kinds of tape to empirical strength and stiffness results and allow the students to make recommendations for what kinds of tape to use to achieve specific results.

Within an inquiry through design curriculum, this model of design as investigation is implemented in the instructions to the students. These instructions encourage students to propose a set of designs that vary in only one feature, predict and explain how they think their designs will perform, develop a procedure to construct and test the designs, record and interpret data from these tests, and reflect on the results with the idea of relating structure — what was varied — to function. The design process also includes a presentation, where students are prompted to explain their results in terms of specific design ideas.

Student reasoning about design results is scaffolded by prompts that ask students to evaluate their designs one design property at a time. Evaluating overall performance can become complex and often involves weighing the effects of multiple factors such as strength, weight, and cost. By focusing on individual properties, students can develop a set of simpler claims, based on evidence, that they can use to reason about overall performance. For example, students may determine that one fishing pole design is the strongest, while a different design variant is the most flexible.
Finally, design investigations can do more than allow students to relate structure to function. Empirical design often leads in surprising results that shape new questions for students to explore. Written prompts leverage the tendency for new factors or ideas to emerge as students build and test their designs. Student questions that result from observation (why did it break there) and comparison (why did your design do better than mine) become fodder for later investigations.

2.2.4 Opportunities for Iterative Design

Inquiry through design also emphasizes the role of iteration in design. Through redesign, inquiry through design provides opportunities for students to investigate multiple design ideas over time. This serves three purposes. First, Schauble has shown that even in cases with minimal instruction, repeated cycles of design led to better experimentation (Schauble, 1990). Providing more scaffolded opportunities for students to engage in inquiry will likely improve their investigation skills.

Second, iteration allows students to critically evaluate design ideas from other groups as well as their own, providing a greater pool of evidence to inform their design decisions. Written prompts help students to critique each others’ design explanations and reflect on how these ideas could contribute to one’s own design. This provides another opportunity for students to use evidence to reason about their designs; the prompts scaffold this process.

Finally, iteration allows students to apply what they have learned to improve their designs. Typical classroom experiments consist of a single trial. The results of this experiment are written up in a lab report and rarely used. Students may be asked to reflect on the implications of what they learned, but rarely do they have an opportunity to use what they have learned to achieve a meaningful goal. In contrast, design projects are rarely successful in their first iteration. Instead, designers iterate again and again, drawing on the results of previous trials to inform new and better designs. Iterative redesign allows students opportunities to investigate questions that emerge from their initial design testing. Surprising and unexplained results thus become fodder for future investigations, as students seek to explain why a particular design idea produced an unexpected result.
2.3 Challenges Facing Inquiry Through Design

While inquiry through design holds promise for supporting student inquiry, it also raises some concerns. In this section, I raise some obstacles that this approach may face in helping students to ask questions, plan investigations, reason with evidence, and pursue explanations.

**Asking questions.** A major challenge for inquiry through design is to help students to frame questions that require sustained investigation, rather than questions that can be quickly answered or questions that require more time, knowledge, or resources than are available in the classroom. We will see whether questions framed within a design context prove to be suitable for such investigations. Another important challenge is to help students to recognize that developing causal explanations for design performance and generating empirical evidence to support these explanations are worthwhile approaches to answer these design questions.

**Planning investigations.** Inquiry through design faces two main challenges to supporting student planning. First, ITD must encourage students to be planful in the face of a bewildering array of possible design choices. It can be tempting to simply explore a series of unrelated design ideas rather than setting out a specific course of action and sticking to it. In addition, the nature of design projects is such that design ideas may emerge from the design process itself, leading students to adopt new ideas that compromise their experimental design.

Second, students need to be able to plan investigations that will yield evidence that stands up to scientific critique. The large number of design ideas present in the design project may lead students to pursue too many ideas at once, leading to conflated experiments. Students may also take shortcuts in experimental design in order to pursue more ideas over time, resulting in evidence that is prone to confirmation bias. Finally, even in well-designed experiments, students may have trouble interpreting data — especially data collected over a series of design trials — and reasoning about the impact of particular design ideas. Inquiry through design must support student reasoning about the data that results from their investigations.
Reasoning using evidence. The ease with which students generate data in the course of a design project raises several challenges for inquiry through design. In addition to generating quantitative data through formal testing, students frequently engage in less formal, qualitative testing as they explore design ideas and decide which ones to pursue in depth. This informal testing helps students to navigate a large space of design ideas, but it is also subject to many of the concerns I have raised about supporting student investigation. Few of these decisions are documented, and many of these quick tests, which are only performed on a single design, lend themselves to reasoning errors such as false inclusion (Kuhn, 1993; Schauble et al., 1991b).

In addition, although individual student investigations are highly scaffolded, there is less support for reasoning about the results of multiple investigations or the results of other groups. Students may be faced with the challenge of reconciling evidence from iterative trials as well as data from other students’ work. A major question to be explored is how often, and how well, students use data to evaluate other students’ design ideas. For example, a student may adopt other student’s idea simply because the other student says it works, rather than critically reviewing the evidence that exists to support the idea. Students must know not only how to evaluate claims based on data, but also when such evaluation is necessary. One consequence of this issue is the importance of fostering goals that encourage students to use data to support explanations of design performance, rather than simply valuing performance itself.

Pursuing explanations. Inquiry through design attempts to balance the intrinsic performance goals of the design context with explicit activity structures, assessment models, and written prompts that all stress explanatory goals. An important aspect of the research described here is to document how students are able to balance the tension between these two goals.

2.4 Summary

Inquiry through design is an approach to curricular design that leverages the affordances of design contexts to engage students in scientific inquiry, while providing targeted support to help students overcome challenging obstacles to successful inquiry (see Table 2.3). This approach informed the development of the Materials World Modules, a series of materials
science units that feature a series of staging activities followed by a culminating design project.

<table>
<thead>
<tr>
<th>ITD Element</th>
<th>Inquiry support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Staging activities</td>
<td>• Provide background knowledge to inform student questions</td>
</tr>
<tr>
<td></td>
<td>• Model design investigation</td>
</tr>
<tr>
<td></td>
<td>• Model design explanation that relates structure to function</td>
</tr>
<tr>
<td></td>
<td>• Provide empirical results students can use to reason about later design decisions</td>
</tr>
<tr>
<td>Authentic design challenge</td>
<td>• Leverage student experience through authentic contexts</td>
</tr>
<tr>
<td></td>
<td>• Encourage design explanations that relate structure to function</td>
</tr>
<tr>
<td></td>
<td>• Encourage consideration of multiple design ideas</td>
</tr>
<tr>
<td></td>
<td>• Generate empirical data</td>
</tr>
<tr>
<td>Design cycle structured as an</td>
<td>• Frame the design project around the investigation and explanation of design ideas</td>
</tr>
<tr>
<td>investigation</td>
<td>• Use written prompts to support planning and conducting comparative investigations</td>
</tr>
<tr>
<td></td>
<td>• Use design process as a source of new design questions</td>
</tr>
<tr>
<td>Opportunity for iterative redesign</td>
<td>• Provide additional opportunities for investigation</td>
</tr>
<tr>
<td></td>
<td>• Let students learn from each other</td>
</tr>
<tr>
<td></td>
<td>• Provide opportunities for students to apply their understanding to improve designs</td>
</tr>
</tbody>
</table>

While inquiry through design provides support for student inquiry in a number of ways, it remains to be seen whether, given these supports and the outstanding issues raised in this chapter, students are able to successfully engage in inquiry.

I am particularly interested in understanding how students engage in inquiry within this design context. How are these curricular units enacted in the classroom? What does student inquiry look like in this setting? What kinds of questions will students explore? Can the
design cycle be a useful model for student investigation? How well do students balance performance goals and explanatory goals?

I situate my research within the classroom in order to focus on two complementary facets of this question: characterizing student inquiry with respect to the challenging aspects of inquiry I have raised; and characterizing practice by examining the particular strategies teachers use to support student inquiry within a design context. In the following chapter, I will describe in detail how I will explore these questions by studying classroom enactments of inquiry through design projects.
Chapter 3. What Does Inquiry Through Design Look Like in Practice?

3.1 Introduction

*Inquiry through design* (ITD) is a model for curriculum design that includes specific kinds of tasks and support to engage students in scientific inquiry. I have argued that it is a means to better engage students in four challenging aspects of doing inquiry: asking questions, planning investigations, reasoning with evidence, and pursuing explanations.

The main research focus of this dissertation is to assess the nature of student inquiry in ITD settings and explain how student inquiry is supported in the classroom. I argue here that to do this, one must study student inquiry in realistic classroom settings and pay particular attention to the role of the teacher in supporting student inquiry. I will describe the context and methodology for three related studies that comprise the research reported in the remaining chapters.

3.1.1 Investigating Inquiry Through Design in Realistic Classroom Settings

Inquiry through design is an instructional framework structured to support student inquiry. The ITD approach has informed the development of several curricular units: the Materials World Modules. Although these units reflect elements of inquiry through design, to understand the role of inquiry through design in supporting student inquiry, I will examine its impact in realistic classroom settings. I adopt this position for several reasons.

First, there is ample historical evidence that curriculum-based reforms have failed to translate into reform-based practice. These include reviews by Cuban and Cohen that describe the ways in which *written curriculum* — instruction represented by printed words on a page — is transformed into *taught curriculum* — instruction represented by what actually happens in a classroom (Cohen, 1988; Cuban, 1990; Cuban, 1993). Although innovative pedagogical approaches may be reflected in printed materials, these approaches do not always translate to classroom practice. Thus, we cannot evaluate the impact of
inquiry through design solely based on how well written the Materials World Modules are. Instead, we must consider how these units are taught.

This view is consistent with research that has examined the nature of inquiry in science classrooms and has found that materials written to support inquiry often do not result in inquiry in classroom settings. For example, teachers’ efforts to adapt materials to meet their instructional goals may result in changes to the written curriculum that are more or less faithful to the designers’ original intent (Welch, 1981). Viewed more broadly, these studies reinforce a troubling gap between research and practice: ideas that emerge from the research community and that are represented in written materials fail to translate into teaching practice (Kennedy, 1997).

The written Materials World Modules may reflect an ITD-based approach, but do not dictate the nature of practice in the classroom. Students may ignore written prompts intended to foster prediction or reflection. Teachers may modify the nature of the design project to better fit with existing classroom norms or available time. These changes, from how curriculum developers intended the material to be used to how students and teachers in the classroom interacted with the ideas and physical artifacts of the instructional materials, reflect the transition from a written curriculum to a taught curriculum.

Second, recent characterizations of classroom practice take care to point out that instructional materials are but one factor that contributes to the nature of practice. For example, Ball and Cohen characterize practice as an ongoing negotiation among three factors: students, the teacher, and the instructional materials (Ball & Cohen, 1996). Each of these factors interacts with the others, implying that even when instructional materials are held constant, variation in teachers, students, and the resulting classroom context will contribute to a unique taught curriculum. This view suggests that any attempt to document the effectiveness of an instructional approach must do so within a classroom context in order to understand the relationships among these three factors.

Finally, it is important to study inquiry through design in realistic classroom settings that represent typical classroom practice. Krajcik et al. (1998) argue that although several recent research projects have demonstrated great success engaging students in inquiry in the classroom, these studies have often been based in classrooms where researchers, graduate students, and other educators provide additional training, support, and tutoring that is not
available in a typical setting where one teacher is responsible for thirty or more students. These researchers question the long term viability of such programs as they expand from initial hothouse settings to more typical practice. Research based solely in highly scaffolded settings faces serious threats to external validity if it cannot demonstrate that such instruction can scale to more typical classroom settings (Eisenhart & Howe, 1992).

3.1.2 Describing and Assessing Inquiry Through Design: Research Questions

My work focuses on understanding how inquiry through design works as a taught curriculum. It is more important to understand how students experience ITD than it is to analyze how the written form of the Materials World Modules embodies this approach. By setting the research in the classroom, where teachers as well as instructional materials contribute to student learning, I have framed two main research questions for this dissertation.

My initial research question, which I explore in chapter 5, seeks to describe and assess how students engage in challenging aspects of inquiry — asking questions, planning investigations, reasoning with data, and pursuing explanations — within an inquiry through design context.

Ultimately, this question seeks to show whether ITD works. To what degree can students engage in these difficult aspects of inquiry? How does a scaffolded design context help or hurt this process? This question also seeks to characterize the nature of student inquiry in design contexts. What does successful inquiry look like in design contexts? How does it differ from inquiry in more traditional science settings? Understanding the nature of ITD in practice is an equally important goal.

My second research question, which I explore in chapter 6, seeks to describe and assess the role of the teacher in supporting student inquiry in design settings and to identify specific instructional strategies used to support asking questions, planning investigations, reasoning with data, and pursuing explanations.

This question acknowledges the role of the teacher in shaping and supporting the taught curriculum, and seeks to identify particular teaching strategies that contribute to successful student inquiry. The relevance of this question is based on Ball and Cohen’s view of classroom practice as negotiated among students, teachers, and the instructional material (Ball & Cohen, 1996). The strategies that teachers employ are shaped by their own previous
experiences with the written curriculum, their interactions with their students, and their responses to events and issues that emerge in the classroom itself. In this way, observing and documenting teaching strategies — and the contexts in which they are used — provides insight into the negotiation of a taught curriculum designed to support student inquiry.

3.2 Three Studies of Realistic Classroom Practice

I base my research on three studies of classroom use of ITD curricula. Each case documents one teacher’s use of a Materials World Module in the classroom (see Table 3-1). In two of the cases, the teacher used the Composites Module (Hsu et al., 1996). In the third, the teacher used a module called Concrete: An Infrastructure Material (Biernacki & Walhof, 1998). Both units are Materials World Modules projects developed using the principles of inquiry through design. (See Appendixes A and B, respectively, for more information about each of these Modules.)

<table>
<thead>
<tr>
<th>Teacher</th>
<th>School</th>
<th>Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lillian</td>
<td>Greenwood High</td>
<td>Composite Materials</td>
</tr>
<tr>
<td>Rachel</td>
<td>Eastgate High</td>
<td>Composite Materials</td>
</tr>
<tr>
<td>Doug</td>
<td>New Bedford High</td>
<td>Concrete: An Infrastructure Material</td>
</tr>
</tbody>
</table>

The classroom studies intentionally span a range of realistic classroom contexts, ranging from a teacher who had never used inquiry through design to a teacher who co-authored the curriculum. This approach acknowledges that there is no single “average classroom,” and was intended to generate naturally occurring contrasts among the way ITD was enacted in each classroom in order to highlight different components of the ITD approach.

In all classrooms the researcher adopted a non-teaching role and offered suggestions about classroom practice only when directly asked by the teacher. This approach was consistent with the goal of documenting practice in realistic classroom settings; substantive support provided by the researcher to either teacher or students during the project run would have constituted a threat to the study’s external validity. Furthermore, a central research goal was
to see how teachers adopted the modules to fit their own practice, and what strategies emerged to support student use of evidence in this context.

In each study, a researcher was present for the duration of the module, which ran from one to three weeks. Videotape and field notes were used to document classroom activity during the unit, and student work — including physical design artifacts, design log sheets, and final reports — was collected and archived whenever possible. Students and teachers also participated in interviews following the unit. (See Appendix C for interview protocols.)

Students participated in semi-structured interviews in which they described the goals of the project, explained their designs, retraced the design process, discussed how their results informed their understanding of their design, explained what they learned from the unit, and compared the design project to other science activities.

Teachers participated in ongoing discussions with researchers in order to document what they saw as the benefits and obstacles of the design project. After the project, they participated in semi-structured interviews in which they addressed their goals for the project, their reflections on how it went, their assessment approach, and their assessment of whether inquiry occurred and their role in making that happen. Finally, teachers were invited to comment on what they might do differently were they to teach the unit again.

### 3.2.1 Lillian’s Classroom

Lillian was a fourth year chemistry teacher in a suburban high school in the Midwest. She taught a standard-level chemistry class consisting of a mix of sophomores and juniors. Lillian was co-author of both the Composites module and the Concrete module. She had taught Composites twice before, was quite familiar with the material, and had experience teaching design-based projects.

Lillian used the Composites module, which focuses on the design of composite materials. Composite materials consist of two or more constituent materials in such a way that the resulting properties of the composite are distinct from the individual materials. The design project for this module challenges students to design a prototype fishing pole, made of a composite material, that is strong, flexible, and light.
Within the classroom, observation focused on one specific group of students. The selection of the group was negotiated with the teacher, with the goal of picking a group of students that would stay on task and be generally representative of the class.

I chose to follow a single group closely over time so that I could study the group members’ design decisions in light of past actions and experiences that the group engaged in. Videotape captured class discussions and this group’s design efforts. Students’ design artifacts were collected at the end of the unit, and students’ final presentations of their work were videotaped. The three students in the group participated in interviews following the unit.

Due to a miscommunication, students’ final reports were not collected. However, all groups’ work was documented by videotaping two presentations — one before students built their first designs, and one at the end of the project — in which each group described their designs and design results. Interactions of group members with other students in the class also provided opportunities to compare the targeted group’s design ideas with those of other groups. Finally, to document the teacher’s perspective on the unit, Lillian participated in a two-hour group debriefing interview following the unit.

3.2.2. Rachel’s Classroom

Rachel was a veteran science teacher in an urban high school just outside a large Midwestern city. She used the Composites module in her accelerated chemistry/physics class. This was a sophomore level class that met every day for a double period. The class alternated between chemistry one day and physics the next; Rachel taught the chemistry portion of the class. Rachel had taught the Composites module once before, and had attended a one week summer workshop on the Materials World Modules.

As in Lillian’s classroom, my observations centered on one particular group of students selected by Rachel as generally representative of the class. This group was followed over time using the same data collection methods as in Lillian’s classroom. The three students and Rachel participated in interviews following the unit.
3.2.3 Doug’s Classroom

Doug was an experienced chemistry and biology teacher at a suburban high school near a large Midwestern city. He used the Concrete module in his regular level chemistry class. Doug had collaborated with education researchers before, but only in his biology classes. This was his first experience using a Materials World Module.

The Concrete module (described in more detail in Appendix B) explores the materials that make up concrete: cement, water, small aggregate (sand) and large aggregate (pebbles). Students explore how differing ratios of these constituents and reinforcing materials such as metal result in concrete with varying properties of strength and brittleness.

The design project for this module was student-centered. Each group of students chose an object to design using concrete, set criteria for the object to meet, and then planned, built, and tested their designs. Because this process resulted in several different design projects, I decided to follow multiple groups in order to see whether the additional step of selecting a design challenge contributed to student engagement in inquiry through design.

With Doug’s help, I selected four pairs of students to follow. These pairs were chosen to represent a range of student ability across the classroom. Research observations rotated among these groups over the course of the project, and the eight students and Doug participated in interviews following the unit.

3.3 Constructing and Analyzing Narrative Cases

To facilitate analysis of student inquiry, I used the data collected from each study to build narrative cases of student design. These narratives, based on classroom observations, videotape, interviews with students and teachers, and reviews of student work, track groups from the introduction of the design project through to the final redesign. They summarize the design decisions students made, the resources on they used, and the interactions they had with other students and teachers over the course of the design project.

Because of the particular data collection methods employed, the descriptive cases from Lillian’s and Rachel’s classes are substantially richer than those from Doug’s. This was a direct result of the decision to follow multiple groups of students in Doug’s class; the study lacked sufficient resources to document fully four groups’ design efforts in parallel.
However, each group was studied in sufficient detail to provide a rich description of their final series of design variants and to document the rationale behind their design decisions. In Doug’s classroom, a gain in breadth offset any loss of depth.

To construct these cases, I used a multi-stage process modeled after Carspecken and Apple’s approach to critical qualitative research (Carspecken & Apple, 1992). Initial data collection provided raw data documenting student activity over the course of the project. This data was then used to construct descriptive chronological cases for each group, using an iterative review approach to identify key events via videotape and field notes (Erickson, 1992).

Case construction focused primarily on the design process within the group. Interactions between groups and interactions with the teacher were reviewed with respect to their contributions to the group’s design project (e.g. were design ideas exchanged, was evidence shared, did students make claims about design performance, etc.). Interactions that did not appear to contribute the design process, such as purely social exchanges or discussions of non-design-related work, were omitted from the cases.

Within this interpretive framework, I viewed each group’s engagement in the design project as a series of design investigations. Each investigation was centered on one or more design decisions about specific design ideas. Organizing the descriptive cases around descriptions of the elements of design investigation — how students resolved questions about new design ideas or new evidence through argument, experiment, whimsy, or other means — provided the necessary structure to guide development of the case and identify key events.

I then wove initial interpretations of specific student decisions and actions into the case, yielding what I call narrative cases (as opposed to simply descriptive cases). My interpretations were guided by a core set of questions that relate directly to the four aspects of inquiry that I sought to document (see Table 3.2). This approach of relying on guiding questions to inform interpretation is similar to Krajcik et al.’s work documenting specific challenges students face engaging in inquiry in project-based settings (Krajcik et al., 1998). Inquiry through design presents specific supports for student engagement in inquiry. The analyses here seek to describe the nature of inquiry in such a context as well as explain how specific factors contribute to student inquiry.
TABLE 3.2.
QUESTIONS THAT GUIDED DEVELOPMENT OF NARRATIVE CASES

<table>
<thead>
<tr>
<th>Inquiry aspect</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asking questions</td>
<td>• What kinds of questions do students ask?</td>
</tr>
<tr>
<td></td>
<td>• What are the sources of student questions?</td>
</tr>
<tr>
<td></td>
<td>• What kinds of questions do students explore?</td>
</tr>
<tr>
<td></td>
<td>• How did teachers support student questioning?</td>
</tr>
<tr>
<td>Planning investigations</td>
<td>• What kinds of investigations do students plan?</td>
</tr>
<tr>
<td></td>
<td>• Do student experiments support comparative analysis/inform the question at hand?</td>
</tr>
<tr>
<td></td>
<td>• What factors affect investigation planning?</td>
</tr>
<tr>
<td></td>
<td>• How did teachers structure and support student investigations?</td>
</tr>
<tr>
<td>Reasoning using evidence</td>
<td>• How do students use qualitative and quantitative data to inform their design understanding?</td>
</tr>
<tr>
<td></td>
<td>• What forms of data do students draw on to make design decisions?</td>
</tr>
<tr>
<td></td>
<td>• What factors affect student data analysis?</td>
</tr>
<tr>
<td></td>
<td>• How did teacher scaffold student reasoning?</td>
</tr>
<tr>
<td>Pursuing explanations</td>
<td>• What kinds of goals drive student design and investigation?</td>
</tr>
<tr>
<td></td>
<td>• To what extent is student inquiry compromised by performance goals?</td>
</tr>
<tr>
<td></td>
<td>• What other factors affect the adoption of explanatory goals?</td>
</tr>
<tr>
<td></td>
<td>• How did teachers contribute to student interest in explanation?</td>
</tr>
<tr>
<td>General inquiry strategies</td>
<td>• How did teachers structure the taught curriculum to support student inquiry?</td>
</tr>
<tr>
<td></td>
<td>• What roles did teachers adopt to support student inquiry during the design project?</td>
</tr>
</tbody>
</table>

I refined the narrative cases by drawing on additional evidence, including transcriptions of student and teacher interviews and copies of student work, to test the assertions implicit in
my original interpretations. I subjected interpretations present in the case to triangulation from these other data sources. Supporting evidence was incorporated into the narrative; disconfirming evidence led to the removal of unsupported assertions.

The resulting narrative cases combine detailed description of student activity with interpretation of that activity and serve as the main corpus of data for my analyses of student inquiry and teaching strategies. These cases have several advantages over the raw data. They provide a chronologically indexed record of student activity, making it easier to compare student decisions and actions to prior and future events. They are detailed enough to support close analyses of interaction critical to explaining how interactions contribute to teaching and learning (Erickson, 1992). They provide access to currently accepted interpretations about student inquiry and help to uncover relationships among classroom factors. Finally, because these cases follow students over the course of the project, they present a chronology of student and teacher activity, allowing inferences about the relationship between goals and action to be drawn.

3.4 Analyses of Inquiry Through Design in Practice

My analyses of student engagement in inquiry, and teacher support for inquiry, that appear in the next few chapters draw heavily on these narrative cases to inform more general claims about student success engaging in inquiry and about teaching strategies that contribute to student success. I will address descriptions of specific analyses — for example, how to document successful student planning of scientific investigations — in these chapters. Here, I will discuss the relationships among these analyses and present a road map for the remainder of the dissertation.

3.4.1 Setting the Context

Chapter 4 provides a short overview of the three classroom studies. This chapter is intended primarily to familiarize the reader with the students and teachers in each classroom, thus providing context for the analyses that follow in later chapters. The descriptive cases that comprise this chapter are edited versions of the original descriptive cases, and are intended to provide sufficient, but not excessive, detail to understand the kinds of decisions and actions students engage in during design.
3.4.2 Describing and Assessing Student Engagement in Inquiry

Chapter 5 addresses my first research question and contains analyses of student engagement in inquiry. These analyses seek to describe and assess student inquiry across the challenging aspects of inquiry that I have described: asking questions, planning investigations, reasoning with evidence, and pursuing explanations.

The resulting characterizations of student inquiry do not claim that all students can productively engage in inquiry in design contexts. Rather, my results serve to highlight the specific challenges students face when asked to blend science and design in a particular way. Within this context, I will discuss the role of specific instances of support and relate these instances to the curricular model of ITD, keeping in mind that curricular materials are but one contributing factor to the classroom enactment. These results may inform researchers, teachers, and curriculum designers who seek to explore and support design as a productive context for inquiry.

3.4.3 Describing and Assessing Teacher Support of Inquiry Through Design

Chapter 6 addresses my second research question and focuses on the contributions of the teacher to student engagement in the four aspects of inquiry. These analyses of teaching practices are also based on the narrative cases, but extend in scope to capture the decisions teachers made while planning the unit that helped frame the curriculum as it was perceived by the students. Interviews with teachers, in which they described their goals for the project and discussed decisions that shaped the project, helped to clarify how teachers transformed the written curriculum into a taught curriculum and where teachers enhanced or adapted the support inherent in ITD.

The resulting characterization of strategies for supporting student inquiry through design form a collection of potential approaches, each contextualized through the goals and experience of a teacher. In fact, one can think of the task of teaching inquiry through design as a design challenge in itself: the design of teaching practice to support student inquiry. Because of the limitations of the written curriculum, teachers must adapt inquiry through design to their own practice. This process is an ongoing negotiation among the teacher, the students, and the written materials (Ball & Cohen, 1996). The analyses in this chapter reflect the ways in which the teachers’ contributions to classroom practice are shaped by their own
experience, their interactions with their students, and their previous experience using inquiry through design curricula.

By observing teachers engaging their students in inquiry, we can document specific teaching strategies for supporting inquiry and so begin to construct a model of how different teaching strategies support student inquiry in different 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.

3.4.4 Revisiting Inquiry Through Design

Finally, in chapter 7, I will reflect on these results and compare the proposed affordances of ITD (from chapter 2) to evidence of successful student inquiry and effective teaching strategies. Based on these results, I will revisit inquiry through design, proposing specific scaffolds and strategies that may need to be incorporated, either by curriculum developers or teachers, to better support student inquiry in design settings.

3.5 Summary

In order to assess the strength of inquiry through design as a model for curriculum design, we must turn our attention to classroom practice. My analyses focus on two main goals: describing and assessing student inquiry in a classroom design context and describing and assessing the teaching roles and strategies for supporting student inquiry. In both cases, I view inquiry in terms of four challenging aspects: asking questions, planning investigations, reasoning with evidence, and pursuing explanations. These research questions reflect my view of classroom practice as an ongoing negotiation among students, the teacher, and the instructional materials. My analyses of teaching practice in particular focus not only on what teachers do to shape classroom practice and support inquiry, but also on how elements of the classroom context, such as the teachers’ goals, their prior experience with ITD curricula, their interactions with students, and their reactions to emergent issues, help shape teachers’ strategic decisions themselves.

The data for this study come from three classrooms that represent a range of teacher experience with ITD. The interpretive framework for constructing these cases focused on
student design decisions and the design process. For each study, I used classroom data to construct a narrative case that layers description and interpretation over a chronological record of one group’s design experience. The analyses that follow will draw on these narratives for evidence that supports or refutes claims about student inquiry, teaching strategies, and the role of inquiry through design.

The next chapter presents descriptive cases from each of the classrooms and provides context for these later analyses.
Chapter 4. Design in Action: Descriptive Cases of Student Engagement in Inquiry Through Design

4.1 Introduction

This chapter serves as a bridge between the theory and methodology of inquiry through design and my examination of the effect of inquiry through design in classroom settings.

The three cases that comprise this chapter describe, with minimal interpretation, the events and actions of students engaged in inquiry through design projects. The cases serve two purposes. First, they illuminate my descriptions of inquiry through design in chapter 2 by showing students participating in inquiry through design: planning, building, testing, arguing about design ideas, and struggling to make sense of evidence. The shift from the written to enacted curriculum is never so apparent as when one watches students stream into an empty classroom; these cases make the experience of inquiry through design more real for the reader.

Second, these cases introduce in detail the students and teachers whose experience with inquiry through design form the core of the analyses that follow in chapters 5 and 6. These cases are condensed from richer case narratives, described in chapter 3, that I compiled from a range of sources, including field notes, videotape, interviews with students and teachers, and copies of student work. Intended to provide context for the analyses and interpretation that follow, the cases themselves are primarily descriptive.

The first two cases, taken from Lillian and Rachel’s classrooms, provide in-depth accounts of how a group of students engaged in the fishing pole design project (part of the Composites Module). These stories allow us to trace student design over time and consider the influence of early actions and decisions on later work.

The third case, which characterizes student engagement in the student-directed design project (part of the Concrete Module) in Doug’s classroom, is slightly different. This case describes the work of two groups of students, selected from four groups that I followed. These two groups represent a range of engagement in design. The methodology for this case study followed four groups broadly over time and is not as rich as the first two cases.
because no group was under observation throughout the entire project. However, the
description suffices to provide an understanding of the nature of each group’s design
investigations and to serve as a comparison to the two Composite classrooms.

4.2 Lillian’s Classroom: Sarah, John and Kathy

Sarah, John, and Kathy were juniors in Lillian’s chemistry class. They participated in the
fishing pole design project, part of the Composites module. The design project took place
over six days (see Table 4.1). Students spent the first three days proposing and building
their designs. Before testing these designs, each group presented their design ideas to the
class. The groups tested their designs the following day and spent the final two days
redesigning their fishing poles.

<table>
<thead>
<tr>
<th>Day</th>
<th>Activities</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Hunting for Composite Materials (homework)</td>
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<tr>
<td></td>
<td>Testing Different Kinds of Ice</td>
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<td>Testing a Foam Composite for Strength and Stiffness</td>
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<td>Designing a Fishing Pole: Introduction and brainstorming</td>
</tr>
<tr>
<td>2</td>
<td>Plan and build first designs</td>
</tr>
<tr>
<td></td>
<td>Grading rubric introduced</td>
</tr>
<tr>
<td>3</td>
<td>(Most of period spent on unrelated activity)</td>
</tr>
<tr>
<td></td>
<td>Groups present their designs</td>
</tr>
<tr>
<td></td>
<td>Discussion of how to test designs</td>
</tr>
<tr>
<td>4</td>
<td>Finish building and test designs</td>
</tr>
<tr>
<td>5</td>
<td>Reflect on results, begin redesign</td>
</tr>
<tr>
<td>6</td>
<td>Finish building and test redesign</td>
</tr>
<tr>
<td></td>
<td>Final presentations</td>
</tr>
</tbody>
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4.2.1 Day 1: Introducing the Design Project

Lillian introduced the design project on a Friday, asking her students to read the
introductory text in the written curriculum. This text outlines the primary design challenge.
Catch More, a fishing supply company, is holding a contest for the design of a new fishing pole. The winning fishing pole will be made of a composite material. Enter the contest and take up the design challenge!

Your group will be given a set of drinking straws to use as a base for your prototype design. With your group, you will design, construct, and test a set of prototype fishing poles; after you evaluate your design and have it critiqued by others, you will have an opportunity to redesign your fishing pole based on what you learned from working on your design.

After students read this introduction, the class discussed important attributes for a fishing pole and decided that they would focus on strength, stiffness, and mass. Good fishing poles would be strong, flexible, and light.

Students spent the final ten minutes of the period brainstorming design ideas. Lillian stressed that each group needed to come up with a set of five design variants that differed in one specific way. The group of Kathy, John, and Sarah didn’t brainstorm long. Kathy proposed using pipe cleaners as a reinforcing material on the inside of the straw. Sarah agreed to try it, stating that “it’d also be light.” The group seemed satisfied with their design idea and did not discuss other possibilities until Lillian visited the group. Lillian suggested that the group think about tape as a design material — the students suggested both packing tape and duct tape — and recommended that the group think about how they could bond their composite design together. (An earlier staging activity had emphasized the importance of bonding.)

By the end of the brainstorming session, the group had planned an initial experiment, in which they would build a set of designs that vary the number of pipe cleaners used to reinforce the inside of the straw. They planned to collect materials over the weekend and build and test their designs the following week.

4.2.2 Day 2: Building the First Set of Designs

Monday morning, the group met, and found that Sarah had forgotten to get pipe cleaners and had brought a roll of telephone wire instead. The change in materials forced the students to reconsider their planned investigation. The group had planned to construct five
design variants that contained from one to five pipe cleaners inside each straw. Now they had to decide how using telephone wire would affect their design variants.

At this point, Lillian visited the students, and prompted the students to identify a design variable — they settled on varying the amount of wire they used to reinforce the inside of the straw — and to make predictions about design performance. The group predicted that increasing the amount of reinforcing wire would make the design stronger, but also stiffer. The group also predicted that the best overall pole would have a middling amount of wire, because that would balance the two properties.

Partway through the period, the group had a plan for their investigation as well as a set of predictions, phrased in general terms, for how their designs would perform. Their remaining task for the day was to construct the set of design variants. As this group began to build their variants, a new design constraint emerged. Telephone wire is much thicker than a pipe cleaner. When the group began constructing their variants, the students discovered that only two lengths of wire could fit inside a straw, compared to the five pipe cleaners that they had expected to fit. Since they intended to vary the amount of wire from one to five lengths of the straw, three of their proposed design variants could not be built.

The group addressed this problem by redefining the “amount of wire” that would go in each design variant. Since two wires were the most that would fit, they decided to include fractional lengths (e.g. one quarter, one half, and one and a half) in order to make five variants ranging from one quarter to two lengths of wire. However, moving from lengths of wire equal to the length of the straw to fractional pieces of wire created another problem. Initially, the students had planned to create fractional lengths by splitting the wire lengthwise (e.g. half of an eight inch length of wire is a thinner eight inch wire). In practice, it proved very difficult to split the wire into two exact halves.

John suggested cutting the wires to make fractions (e.g. half of an eight inch length of wire is a four inch length of wire). This led to another issue: what portion of the length of the straw would the fractional length reinforce? The group decided to center the fractional length in the middle of the straw.

When she visited the group, Lillian suggested another design idea. Telephone wires consist of plastic surrounding four smaller colored wires. Varying the number of little wires was an
alternative that avoided the problem of defining fractional wires. Although the students did not adopt her suggestion, their later redesign drew on a very similar idea.

The final construction challenge was to get the second length of wire into the straw. The fit was simply too tight to push through the second wire. To address this problem, the group explored an alternative construction design. They cut the straw lengthwise, laid the wire inside, and then taped the straw back together. The students were aware that this design was inferior and explored it primarily because it offered a solution to the problem of threading two wires into the straw. A design innovation saved the group from having to decide between performance and ease of construction. The group discovered that they could get the second wire into the straw by tying string to the wire, passing the string through the straw, and using the string to pull the wire through. Having solved this pragmatic design problem, the group abandoned the alternative design.

A final modification to the group’s design came because of Lillian’s insistence that the group somehow bond the materials together. To address the bonding issue, the group added glue to the ends of each their design variants, essentially capping the wire in place with glue “plugs.”

This completed the set of design variants that the group would present to the class prior to testing on the following day. The group had five designs that varied the amount of telephone wire inside the straw, with glue capping the ends to hold the wires in place. The group’s predictions for these designs were that the one with the most wire in it would be the strongest and least flexible, and that the one with the least wire in it would be the weakest and most flexible. Since the fishing pole challenge demands both strength and flexibility, the group predicted that the middle design, which they predicted to be somewhat strong and somewhat flexible, would be the best overall fishing pole.

4.2.3 Days 3 and 4: Testing the First Set of Designs

Although the students in the class had by now identified the properties they would test — strength, stiffness, and weight — and built a set of design variants to be tested, they had not yet specified exactly what the tests would be. On Day 3, each group made a short presentation to the class describing their design and sharing their predictions of which design variants would perform the best. Later in the period, Lillian led a class discussion
where students identified three potential means to test their designs. Lillian left it up to each group to decide which method to use.

On Day 4, students immediately split into groups to test their designs. Lillian visited each group to confirm that they had chosen one of the three testing methods discussed the day before and had prepared a data table. John and Kathy (Sarah was absent) initially planned to test their design one way, but switched to another for pragmatic reasons.

The group was surprised to discover that one particular design variant, the design that used two full lengths of telephone wire, turned out to be the strongest and the second most flexible of their designs. They had predicted that this design variant would be the least flexible of the five. John describes the results in a later presentation.

JOHN After testing with the spring scales on each of our straws, we figured out through test one that the best straw was the heaviest straw, which had two straw lengths of wiring. And this kind of shocked us because we thought it’d be a little... it would be too heavy and it would just be strength and wouldn't be... flexible. But to our disbelief, it was, and it proved to be our best straw in our first series.

4.2.4 Day 5: Planning the Redesign

Surprised by their testing results, the group approached the redesign with a specific question in mind. Telephone wire is itself a composite material, consisting of an outer plastic covering that encases four smaller wires, each of which is wrapped in a colored plastic sheath. The students wanted to explore how these components contributed to the strength and stiffness of their design.

As in their initial investigation, the students needed to identify a variable that they would vary across a set of designs. Sarah proposed starting with one big wire and then varying just the number of smaller wires. John disagreed. He wanted to investigate the role of the outer covering, which meant comparing Sarah’s idea to a design that contained only smaller wires. Sarah, however, was concerned that building a design without the outer covering
would sacrifice too much strength. The two students argued their positions based on relationships between their ideas and the target design properties.

The group decided that they could test both John and Sarah’s ideas, but Sarah was concerned that their design variants will end up varying too many things: the number of small wires and the number of big wires. In response, John suggested a plan for varying the number of big and little wires in a consistent way, so that the effect of both materials can be assessed.

SARAH Yeah, except that our variable is now... we have to keep our variable the same, so... (KATHY: Yeah.) if we do all little wires...

JOHN But isn't it all wires? Isn't it still wiring?

SARAH It's the number of little wires.

KATHY The number of thin wires.

SARAH So it's... if we have four thin wires the next time, and six the next time, and eight the next time, blah blah blah blah blah. Then we have to keep going like that. Otherwise, we...

JOHN Well, can't we say that it's thick and thin wires? That vary? I mean this is only...

SARAH But we have to keep it constant. It's not like we can just generally... let's do some this way and some that way.

JOHN You can't change this and the little wires at the same time? You can't say this is zero/eight thin, zero heavy/eight thin and then do one heavy and four thin?

SARAH Oh yeah. We can do that.

TEACHER So that would be the ratio of thick to thin wires. That's your variable?

This discussion resulted in three design variants: one with eight thin wires, one with one thick and four thin wires, and one with two thick wires. Sarah suggested a fourth variant
that “fits the pattern”: a design that would consist of one and a half thick wires bundled
with two thin wires. While this variant was never built, it suggests that the “pattern” for the
investigation was to incorporate all eight thin wires from two big wires and vary the
amount of plastic sheathing. What these variants had in common is that they all
incorporated the number of thin wires that were used in the best performing design of the
first experiment. (That design used two thick wires that contained a total of eight thin
wires.) These variants would help the students determine the effect of the outer covering of
the wire on design performance.

Implicit in these three variants was the notion of a tradeoff between strength and flexibility.
The group believed that the thick wires made the design stronger, while the thin wires
made the design more flexible. So a design that included only thick wires sacrificed
flexibility for strength, and one with only thin wires gave up strength for flexibility. But
what if one could increase both strength and flexibility? To test this, the group built two
more variants that use two thick wires for strength and added one or two thin wires to
increase the flexibility. These two variants, which fit within the scope of the group’s
experimental plan (varying the ratio of heavy to thin wires), completed the set of designs the
group would build and test. Sarah describes the five design variants in a later presentation.

SARAH  OK. In our second tests, we used these... the idea behind our
second tests is that this part of the wire, the white part of the wire,
gave it its strength, and the inside of the wire gave it its flexibility.

And so we decided to tear them apart, and in the first one we used
only the smaller...

JOHN The thin wires.

SARAH Yeah, the thin wires. And then we worked our way up to... what
we did, then we did a thick wire and four thin wires. Then we did...
two heavy ones and one thin one, and then just two heavy ones,
so we could compare it to the other ones.

During the redesign, Lillian introduced two design ideas for the group to consider. The first
idea was to consider incorporating a material, such as tape or plastic wrap, that could be
wrapped around the outside of the straw. She told the group that since they had already
learned something about how to reinforce the inside of the straw, they could use the redesign to think about reinforcing the outside of the straw. The students did try to incorporate tape into one of their designs, but only because, as Sarah put it, they thought that “she wants us to.” When it became clear that Lillian’s suggestion was just a suggestion, the students chose not to use the tape. Lillian’s other suggestion was to skip the variant comprised of one-and-a-half lengths of thick wire and two thin wires. The reason, she argued, was that the straw should be reinforced along its entire length, not just in one specific place. The group did not build this design variant.

4.2.5 Day 6: The Final Tests

On Friday, the last day of the project, Sarah and John (Kathy was absent) tested their redesigns and then spent five to ten minutes reflecting on their results and preparing a short presentation for the class. The group found that the performance of their redesigned fishing poles improved on their previous designs by a factor of two. The students were again surprised by their results, which showed that their fifth variant, which contained two thick wires and one thin wire, displayed the greatest strength and flexibility. Sarah reports their results to the class.

SARAH And it turned out that... then we tested it using the spring scale, and we thought that the strongest one would be the one straw... the straw with two heavy wires and two thin wires, because it seemed like the best of both worlds.

And actually, we were slightly off. The one that was the best was two and one: two heavy and one little one. And we were kind of surprised, because we thought that it wouldn't be that much different from one with just two heavy wires in it because you wouldn't think this [thin wire] would make too much of a difference.

And so we thought it would basically be the same, when actually, they were very similar, but when it came down to it the one with two heavy wires and one thin wire, under a force of 8 Newtons, deflected 12 centimeters, and the other one only, under 7
Newton's, was 11.5. And it broke at that point so you couldn't put any more force on it.

So we kind of found... or, we did find... at the end, that it seemed to us that the more, the higher the mass, the better it was because that's what the trend was throughout our tests.

4.3 Rachel's Classroom: Lisa, Ellen, and Carrie

Lisa, Ellen, and Carrie were sophomores in Rachel’s chemistry class. They participated in the fishing pole design project, part of the Composites module. The class met for ninety-minute double periods each day. Students spent about two and a half days on staging activities prior to beginning the design project. The design project itself took place over three days. Following a brainstorming session on Day 3, students brought in materials, built, and tested their initial designs on Day 4 (see Table 4.2). After the weekend, students spent half of Day 5 building and testing their redesigns. Students then worked on their design logs outside of class and turned them in later in the week.

<table>
<thead>
<tr>
<th>Day</th>
<th>Activities</th>
</tr>
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</table>
| 1   | Testing Different Kinds of Ice  
     | Hunting for Composite Materials  
     | Introduce Researching Composites Paper |
| 2   | Exploring the Difference Between Strength and Stiffness  
     | Testing a Foam Composite for Strength and Stiffness |
| 3   | Geometric Reinforcement  
     | Designing a Fishing Pole: Introduction and brainstorming |
| 4   | Plan, build, and test designs |
| 5   | Plan, build, and test redesigns  
     | Students continue to work outside of class on final reports, due four days later.  
     | Research Composites paper due four days later. |
4.3.1 Day 3: Introducing the Design Project

On Thursday, Rachel presented the design project as a challenge, one in which the class would work together as several collaborative groups. Rather than having students read the written introduction, Rachel introduced the activity herself. In her introduction, Rachel explained how each group would build three prototypes and then one final design based on the results of their initial testing. She then asked the class to identify the properties that they thought were important for the fishing pole. Students suggested the properties of strength, flexibility, and, with some hints on Rachel’s part, weight.

Rachel encouraged students to draw on what they had learned in earlier staging activities. She provided an example of a set of design variants to illustrate what she meant by varying only one thing at a time. She explained to students the method they would use to test their designs, and described how the three target properties would be combined to create a single overall measure (a design ratio) for design performance.

Rachel described the redesign as a chance for students to vary just one thing from their first set of designs or try something completely different. Prior to the redesign, she said, students would share what they had learned. Finally, Rachel outlined her assessment plan and offered extra credit for the best design in all her four classes. The group, and the group’s class, with the best performing design would earn extra credit points.

Rachel gave the students the remaining twenty minutes of the period to begin brainstorming ideas and planning what materials to bring in the next day. Some materials that had been used during an activity on Day 2, including thin rods made from plastic, bamboo, and metal, were available on tables at the sides of the room.

Ellen, Lisa, and Carrie considered a number of ideas during this time. Ellen began by proposing that they use a plastic rod that could be inserted inside the straw to provide support. Ellen next proposed using duct tape to reinforce the outside of the straw, drawing on an earlier staging activity that showed the value of directional reinforcement. Both ideas were accepted.

Ellen’s next idea was more controversial. She proposed using modeling clay to reinforce the inside of the straw. Both Lisa and Carrie disagreed with this idea.
Shortly after the clay discussion, Carrie suggested using pipe cleaners. Ellen argued that pipe cleaners are a bad idea, and mimed how she imagined a pipe cleaner-based fishing pole would bend under stress. The display was sufficient to convince Carrie to drop the idea.

In addition to design ideas, Ellen presented a plan to learn more for their design. She realized that since each group was scheduled to present their results the next day, her group could focus on one specific design idea, and rely on others to provide additional information about how other materials improved a design. Ellen explained her strategy to Lisa and Carrie.

ELLEN Yeah, you know what else we could do though? Is we could just test the inside, and just decide that this is the outside that we like, because they’re going to tell us about outsides tomorrow.

By the end of the period, the group had a general idea of the kinds of materials they wanted to use, but had not committed to a specific investigation or design variable. They planned to wrap duct tape lengthwise around the straw, an idea based on their previous experience with a staging activity. They had several candidates for reinforcing the inside of the straw, including wood, modeling clay (still a contentious choice), and plastic. They also left open the possibility of finding other good materials when they visited a hobby store after school.

4.3.2 Day 4: Building and Testing the First Set of Prototypes

Before groups began work, Rachel informed the class that there wasn’t going to be enough time for groups to present to each other; earlier classes had needed the time to finish building and testing their prototypes. Instead, Rachel created a table on the board with two columns: things that worked, and things that didn’t. She encouraged students to write their findings on the board, so that groups could learn from each other without having to take the time for formal presentations.

Students began group work about fifteen minutes into the period. The girls brought in materials as they had planned: Ellen brought duct tape, Carrie scissors, and Lisa brought plastic rods and wire. Lisa had been to Tom Thumb to search for materials to reinforce the inside of the straw. She had tested several materials in the store before choosing her materials.
The group knew Rachel had said they needed to make three different prototypes. Their plan was to build one prototype, see how that worked, and then design their second and third prototypes based on their initial results. The first prototype used a plastic rod and four thin wires to reinforce the inside of the straw. The group also wrapped duct tape around the outside of the straw, orienting the fibers of the tape lengthwise, as they had decided the day before. While the use of the rod and the wires was planned, the exact number of wires used was a pragmatic decision, based on how many wires the students could fit into the straw.

Once the group had finished building their first prototype, Ellen tried bending the design by hand to assess its performance. Her test showed that the design was fairly flexible and reassured the group that they had a promising design. Ellen commented that if they were to wrap another layer of duct tape around the straw, oriented perpendicular to the existing layer, they might not be able to bend the straw at all. The mass of the design was promising as well: light enough, according to another student nearby, to be a candidate for a good design ratio.

When the students began to test for flexibility, an unexpected problem emerged. The design flexed under strain, but failed the test by failing to return to its original shape: a sign that the design was weaker than they thought.

The students argued over their interpretation of the criteria for failure and the results of their test. Ellen argued that the design “still looks the same,” questioning whether the deformation was permanent. Lisa argued that the design had not returned to its original shape and so was a complete failure because it wasn’t even strong enough to survive the flexibility test.

The group decided that the best way to resolve their argument was to repeat the test. The second test yielded a similar outcome; the design did not completely return to its original shape. This time, the students sought out Rachel to confirm that they were interpreting the strength criteria properly. They were. A third test confirmed the failure of the design.

The particular nature of how their design failed provided direction for the students’ next design variant. When Rachel visited the group later to check on their progress, they explained why they thought the design failed, and what they were looking for in their next design.
CARRIE  Ours is really good. It just didn’t come back.

ELLEN  See, the wires kept the shape.

TEACHER  And that’s what was in there?

ELLEN  Wires and a plastic rod.

CARRIE  Plastic’s really good.

TEACHER  Do you have an idea what you can replace it with?

ELLEN  Bigger wire!

TEACHER  Try to replace just one thing of the design.

Ellen’s statement that “the wires kept the shape” reflected the group’s diagnosis of the major problem with their design: wires bent, and did not bounce back. To address this, the group planned to replace the wire with a material that would not bend like wire.

The group considered several materials for their second design variant. Lisa considered a length of fiber optic cable, which the group sharing her lab table had brought. Ellen was trying to build her own design idea, which was to pack the inside of the straw with modeling clay. Lisa and Carrie were skeptical of this idea.

LISA  Then why are we testing it?

ELLEN  Because it might work. If you put wire in too.. it might help keep its shape.

LISA  I mean, but look at clay. See? (Bends a piece of clay.)

In spite of Lisa’s graphic demonstration, Ellen persisted in her design. Lisa was willing to let it be their second prototype, and she began work on another design idea that would be the third prototype of the day. Another group had told her that wet wood worked well, so she began cutting lengths of bamboo skewers to fit inside the straw. Carrie went up to check the board where students had been writing down which design materials worked and which did not work. She reported to the group that, based on the board, “wire, wrap, and wet bamboo” did not work. Because of this report, Lisa abandoned the wet wood idea that she had been working on.
Lisa reconsidered the fiber optic cable, and asked the group that brought it if they had any left over. They said no. This left Lisa and Carrie searching for some material that might help the straw keep its shape. Ellen continued to work on her clay idea despite the skepticism of the other two students. Finally, exasperated by their comments, Ellen challenged Lisa and Carrie to help her finish building her design so that they could test it and let the results decide the issue. Lisa and Carrie agreed and began to work with Ellen on her design. Lisa remained convinced that the design idea would not work and made one final argument against clay, this time providing an explanation that related the properties of the clay to the needs of their design.

LISA No, I don’t think it would work.

ELLEN Why not?

LISA Because clay has no values that are helpful to us.

ELLEN It keeps the straw from crimping.

LISA No it doesn’t. Oh, duct tape keeps the straw from crimping. We don’t need to keep the straw from crimping, our original design never crimped. That’s not our problem. We don’t want to solve problems we don’t have.

The issue was at last resolved when difficulty pushing the clay into the straw and Lisa’s final argument convinced Ellen to abandon the idea.

In the meantime, Lisa and Carrie had searched for another material to use in their design. They returned to the fiber optic cable that the other group was using. After some haggling, Lisa bought a length of the cable for a dollar. Lisa replaced some, but not all, of the wires with the cable. This meant that the group was varying two materials at once: the amount of wire and the use of the fiber optic cable. The students were aware that they had just added another design variable, but dismissed it on the grounds that they were still “just testing” different design ideas.

LISA We can’t use another variable.

CARRIE Can we use duct tape?
LISA Yeah...

CARRIE Well we’re just testing, we’re not making our three with one variable, are we?

LISA Yeah, I guess not...

The students tested this second design and encountered what they described as the “same problem.” The straw did not return to its original shape, sending the group back to the drawing board for their third design.

For their third prototype, the group decided to remove the wires entirely and think about another material they could use to reinforce the inside of the straw. They had already considered most of the materials in the classroom, including those they brought, several materials that other groups had brought, and materials that were left over from earlier staging activities. They complained to Rachel that they could not think of any more materials. Rachel first directed the students to review the list on the board, but then gave Ellen a hint: Rachel had “always had good luck with wood skewers.”

The group decided to add wood in place of the wires. However, the wood skewers were too large to fit in addition to the plastic rod, so the students removed the rod. The resulting prototype included the fiber optic cable and two wood skewers inside the straw for reinforcement. The group tested their third prototype just before the end of class, and this time their testing broke the design outright, splintering the wood skewers.

By the end of the period, the group realized that their designs did not meet the project requirements of three design prototypes that varied only one thing. The fact that they had been “just testing” several designs left them behind the project’s schedule. As Lisa put it later, “I’m not sure we really knew what did work and what didn’t work.” The students arranged to meet over the weekend to modify their initial designs so that they varied in only one way and test these design variants.

4.3.3 The Weekend: Redesign with One Variable

Data about this session is limited, since no researchers were present during this impromptu session. However, based on interviews and the group’s written work, it appears that the group used the time as they said, to improve their investigation so that they were testing a
specific variable. The students decided to use the plastic rod and duct tape in each of their design variants, and to vary the particular material that they put inside the design along with the plastic rod. The three materials they chose to vary (wire, fiber optic cable, and wood) were all ideas that they had tested on Friday in different combinations. The results of these tests showed that while the two variants that used fiber optic cable and wood fared well, supporting nine to ten Newtons of force before failing, the variant that used wire failed quite early, under only three Newtons of force. Lisa summed up these results in her log.

Within our three tests we found out that the wires didn’t work. They didn’t bounce back. The fiber optic seemed to work well it was stiff but it moved and bounced back. The wood added stiffness too. The plastic rod was too flexible, and not very strong. We decided duct tape was not strong enough, so we tried to find more reinforced tape.

4.3.4 Day 5: Redesign

Rachel had framed the redesign phase of the project as an opportunity to build a single design, based on what the students had learned during the previous design phase, that would be entered in the design competition. The observed group approached the redesign as a chance to incorporate several of the design ideas that they had investigated over the past few days. Their initial plan followed up on their weekend investigation and mirrored Lisa’s conclusions from her log. They intended to combine the two materials that seemed to work well over the weekend: fiber optic cable and wood. They also planned to remove the materials that they felt were less effective, dropping the plastic rod idea completely and replacing the duct tape with fiber-reinforced (strapping) tape because it was lighter and “more reinforced up and down which were the most important directions for pull.”

As the group discussed the materials they would use, another student told the students that, based on his group’s results, “fiber optic doesn’t work.” The students’ response to this claim was to remove fiber optic cable from their design and to turn their attention to incorporating short pieces of wood inside their straw. This occurred despite the fact that the day before, their own tests had shown that fiber optic cables worked just as well as wood.

Abandoning fiber optic materials left the group focusing on wood, but a problem arose: they didn’t have any pieces of wood similar to the skewers they had used over the weekend.
Instead, they had Popsicle stick-like pieces that were shorter than the straw. Ellen and Lisa disagreed over whether they should use these pieces in their design. Lisa argued that the wood would work because their weekend tests showed that wood worked in their designs. Ellen disagreed, explaining that because the sticks were shorter than the straw, the design would crimp at the point where the wood ended inside the straw.

Ellen’s explanation convinced Lisa, and the group began to search the classroom for wooden skewers that were as long as the straw. The search was unsuccessful, leaving the students’ original redesign idea in jeopardy: the use of fiber optics had been undermined by another student’s claim, and the use of wood was problematic because the students could not find any wood that was similar to what they used in previous trials.

Faced with a lack of time and materials to explore new design ideas, the students resigned themselves to being design competition also-rans. As Lisa put it, “we’re not going to win anyway.” Having given up on the competition, the group decided to build their original redesign idea, using the wood they have available. This design included two different kinds of fiber optic cable (one thick cable and three thinner cables) as well as a wood “skewer” formed by overlapping two shorter lengths of wood. Finally, the students wrapped fiber-reinforced tape around the outside of the design. This design was an improvement over the students’ earlier designs, but it did not come close to winning the competition.

4.4 Doug’s Classroom: Beth and Luke; Lois and Larry

This case provides an important contrast to previous cases in both subject domain and the framing of the design task. Doug used the Concrete: An Infrastructure Material module. Doug chose to have his students do the student-directed design project. In this project, students are asked to come up with their own application for the material they were studying and define for themselves how they will evaluate the success of their design. For example, one group might choose to make concrete flowerpots, while another decides to make concrete shelves. In each case, students must define target design properties and methods to assess these properties.

The class was a mix of sophomores and juniors. Doug created new pairings of students for each new activity during the module. This overview describes the design projects of two of the four study groups: Beth and Luke, and Lois and Larry. Beth and Luke were unusual for
two reasons. First, they were the only group studied who did not evaluate their designs for strength, which was one of the two properties earlier staging activities had emphasized. Second, they provided the best example of a group that explored a new design idea by constructing a series of controlled design variants. Lois and Larry’s activities were more representative of the other three groups. They drew on earlier staging activities for both testing methods and specific concrete formulations, and created multiple design variants to explore multiple design ideas.

Because this study followed multiple groups, I do not provide as detailed a description of a single group’s progress through the design project. Instead, I will focus on the structure of each group’s main investigation and the design questions and use of evidence that surround it.

Students spent five days, scattered over a two-week period, working on staging activities. (Because some activities required waiting for concrete to cure, the activities could not be done over consecutive days.) The students spent five days on the design project and did not do a redesign (see Table 4.3).

<table>
<thead>
<tr>
<th>Day</th>
<th>Activities</th>
</tr>
</thead>
</table>
| Five days scattered over the prior two weeks | Hunting for Objects Made of Concrete  
Comparing Different Kinds of Cements  
Comparing Different Concrete Formulations  
Testing Properties of Concrete  
Reinforcing Concrete |
| 1 | Finish Reinforcing Concrete  
Designing a New Concrete Product: Introduction |
| 2 | Choose design goal, plan first designs  
Assessment discussion |
| 3 | Plan and build designs |
| 4 | Plan and build designs |
| 5 | Finish building and test designs  
Students continue to work outside of class on final reports, due four days later |
4.4.1 Overview of the Design Project

On the first day of the project, Doug presented the design challenge as “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.” Students had to identify a particular item that they wanted to make out of concrete. They had to construct a mold, decide on a concrete formulation (a combination of cement, water, fine aggregate, and coarse aggregate), and build it. And they had to test it. Doug encouraged students to draw on staging activities that had given students experience making molds, mixing concrete in varying ratios, and testing concrete to measure its strength and brittleness.

Students would do only one design cycle. However, Doug encouraged students to be experimental and to make several prototype designs, so as not to “put all your eggs in one basket.” He suggested that students try several concrete formulations as well as drawing on what they learned in two previous staging activities about how several different formulations affected the strength and brittleness of concrete. During the earlier activities, students had documented their results on large posters that now hung in the back of the room. Doug encouraged students to look at these results to help plan their designs.

Because concrete typically takes several days to cure, students rushed to build their molds and mix and pour the concrete by Friday (Day 4) so their designs would have the weekend to cure. On Monday (Day 5), the groups tested their designs in class, and then wrote up their findings in their lab journals over the week.

4.4.2 Beth and Luke

Beth and Luke chose to make miniature cooking pots out of concrete. The only group that did not include strength among their target design properties, the group instead decided that their pots needed to do two things: boil water quickly, and resist cracking, as a glass pot might, when taken directly off a hot stove and immersed in cold water. The students created two straightforward tests to measure these properties: they timed how long it took to boil water in the pot, and then promptly immersed the pot in ice water to see if it would crack.

The group explored two research questions, and built a total of five design variants to support their investigations. The first question focused on how different aggregate ratios might affect design performance. The students had learned in an earlier staging activity that
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a 1:1 ratio of coarse aggregate (pebbles) to fine aggregate (sand) produced the strongest concrete. The students wanted to explore whether this ratio also affected heat conduction. The group explained the goal of their experiment in their final report.

In all of our past experiences, mixtures of coarse and fine have performed best. All coarse mixtures have proved very weak so that may not withstand as well. All fine aggregate mixtures have proved very brittle so that mixture may not work very well. We haven’t done anything in the past concerning heat. Our experiments rely completely on heat conduction so we really have no idea how the mixtures will react.

To explore this question, the students planned to build three design variants to investigate this question: one with all coarse aggregate, one with all fine aggregate, and one with that was a 1:1 mixture of the two.

The group built two extra variants because “...we thought we should get some more products. So, we decided we didn’t want to do anything more with rocks or sand, so we made just two basic cement and water mixtures... just [to] see different mixtures.”

The resulting five design variants were split into two investigations, one more comparative, and one more exploratory. However, an interesting pattern emerged from the students’ data. The students discovered that the two exploratory variants took significantly longer than the other three to boil. This presented the students with a new, unexpected relationship to explain. Examining the available evidence, the pair concluded that “if there is less water in the cement/concrete mold, it boils faster.” While this finding was consistent with their results, the students lacked the evidence to make a strong case because there were too many other variations among the designs. (For example, the lack of aggregate in the two exploratory variants could have been a factor.)

4.4.3 Lois and Larry

Lois and Larry chose a different application for their design project. The pair originally wanted to design a concrete bowling ball, but scaled down to bocce (lawn bowling) balls when they realized how much concrete they would need to fill a bowling ball-sized mold. They used hemispheric molds to create half-balls, which they felt would allow them to evaluate how each ball would perform. Much like Beth and Luke, this group chose to
measure design performance in terms of real world needs. They describe their tests in their final report.

Our first test with our product was to see if it fulfilled its purpose. We put the half-spheres on their side to see if they rolled. The second test was to see if the balls could withstand impact. They needed to withstand impact so that they wouldn’t break if dropped, or when they hit the pins. So we tested for this by dropping the samples from various heights.

While the ability to roll was a novel property, being able to withstand impact related to earlier staging activities that had explored the properties of strength and brittleness.

Much like Beth and Luke, Lois and Larry investigated multiple questions within a single design cycle. The group used five design variants to explore four different research questions. Their initial design applied what they had learned from an earlier staging activity. The class had determined which of a series of formulations produced the strongest and least brittle concrete. The students predicted that the best formulations from those tests would also succeed for their design.

The first question arose from Larry’s disagreement with the interpretation of earlier evidence. In an earlier activity, paper clips had been used to reinforce a concrete brick, and another student claimed that this had improved the strength. Larry disagreed and built two comparable variants, one with paper clips and one without, to test this claim. In an interview following the unit, Larry, one of the group members, talks about his prediction.

LARRY ...someone who had an earlier test on a brick used paper clips and my theory was the paper clips didn’t really help it that much, it was the way they made their cement... with cement and water and the ratio... that worked. But, we just tried it [varying paper clips] to see if it would work better.

Since this experiment required only two design variants, the students had time to build an additional three design variants to explore three unrelated “what if” questions: what would happen if a lot of sand were added, what would happen if only cement and water were used, and what would happen if they increased the amount of cement in one of their earlier
designs. Each of these questions led to a single design variant that represented the hypothesized formulation change. Larry explains these investigations in his final report.

Our third sample was just sort of an experiment to see what would happen to the ball if there were a lot of sand in it. The fourth sample we made out of just cement + water, just to see what would happen. The fifth sample we made with the same amount of sand in the first one, but with a lot more cement.

From a performance standpoint, the pair’s exploratory variants paid off. While the third variant did not pass the rolling test (it fell apart coming out of the mold), the fourth and fifth designs substantially outperformed the first two. The students did not offer an explanation for these results. The performance of the fourth and fifth designs also overshadowed the results from the first two designs, which were intended to compare the effect of reinforcing paper clips. While adding paper clips produced a modest performance gain, the two new designs survived drops from over twice the height of the other variants. The students’ final report focused on the new designs; aside from a brief note in their data table that “the clips held it together,” the pair did not relate the effect of the paper clips to empirical evidence.

4.5 Summary

While more evaluative analysis will follow in coming chapters, the preceding cases show that students were highly engaged in the design task. They participated in complex, open-ended projects, and were able to successfully propose, build and test their own design ideas. Clearly, the use of design has proven to be an engaging context for students.

These cases provide a backdrop for the work of the upcoming chapters, which focus on analyzing both student engagement in inquiry and teacher support of student inquiry. These analyses will refer to events described here, and will expand on specific events where necessary to illustrate how students engage in inquiry in design settings.
Chapter 5. Student Engagement in Inquiry Through Design

5.1 Introduction

The inquiry through design (ITD) approach seeks to provide context and support for engaging students in challenging aspects of scientific inquiry. In chapter 2, I explained how aspects of ITD were designed to allow students to ask questions, plan investigations, reason using evidence, and pursue explanatory goals. Now, we turn to the classrooms described in chapter 4 to determine whether students working within this context were able to engage in inquiry.

5.1.1 A First Step: Successful Student Engagement in Design

The descriptive cases in chapter 4 illustrate the nature of student design projects. Students quickly become engaged in complex, open-ended projects. Students are able to successfully propose, build, test, and evaluate their own designs, indicating that they could succeed in meeting the project’s design goals. Students from Lillian and Rachel’s classes, who had the opportunity to engage in redesign, demonstrated that they could improve their designs over time. Students in Doug’s class showed — much to Doug’s surprise and relief — that they were capable of identifying and pursuing their own design challenges. Further, the design tasks supported a diversity of design ideas: each group pursued their own unique design ideas, and each class as a whole did not converge on a small set of design solutions.

These examples, which are representative of student engagement in design in each classroom, indicate that the projects were quite successful from a design perspective: students were highly engaged in the task and built designs that performed well. However, success at design does not imply success at inquiry. In this chapter, I will investigate the degree to which students were able to engage in successful inquiry while also engaging in design.
In chapter 3, I presented two main research questions for inquiry through design, questions meant to assess, as well as describe, the nature of student engagement in inquiry through design. I will address the first of those questions here. *How do students successfully engage in inquiry while using an inquiry through design curriculum?* I will describe and assess student engagement across four main aspects of inquiry:

- **Asking questions.** What kinds of questions do students generate in design settings? How productive are these questions — do they lead to successful investigations?
- **Planning investigations.** What kinds of investigations do students undertake? Do these investigations lead to scientifically meaningful results?
- **Reasoning using evidence.** What kinds of empirical evidence do students generate? How do they use evidence to reason about their design?
- **Pursuing explanatory goals.** Given their engagement in a design project, how well are students able to make decisions that are consistent with scientific goals? Do students generate explanations for why their designs work?

Inquiry conducted within a design setting may look quite different from inquiry in a more typical experimental setting. For one, students are not limited to a fixed set of choices. As we have seen in chapter 4, students must decide among a wide range of design materials and construction methods to advance their design. Students must make sense of many different, possibly conflicting findings. Since each group is pursuing its own design ideas, students are faced with a variety of empirical design results, only some of which may be applicable to their own design. These differences between experimental and design settings reinforce the importance of describing the nature of student inquiry.

While student inquiry through design may appear different than inquiry in other settings, it has the same goal: to generate and refine explanations for scientific phenomena. To assess student inquiry, I will relate successful student inquiry to particular elements of inquiry through design that I described in chapter 2.
5.1.2 Study Context and Methods: Compiling Narrative Cases

This study is based on three instances of classroom use of inquiry through design curricula. These cases are described more fully in chapters 3 and 4. Two teachers, Lillian and Rachel, used the Composites Module and the fishing pole design challenge in their chemistry classes. In each class, I observed a single group in detail in order to construct a rich longitudinal record of student engagement in the design task.

A third teacher, Doug, used the Concrete Module and its student-directed design project in his chemistry class. Here, I observed four groups in order to document student inquiry across a range of student-defined design projects.

The data I collected included field notes and videotape of classroom practice, copies of student work, and semi-structured interviews conducted with observed students and teachers following the completion of the unit.

As described in chapter 3, I used these data sources to construct a rich description of the observed groups’ design projects. To identify key events in the narrative, I drew on classroom data to search for instances where students made decisions that affected their design or encountered ideas and evidence that related to their design. These moments were used to focus the narrative on instances where students were asking questions, planning investigations, and reasoning with data: all decisions which directly impacted their designs. I used additional data sources, including interviews, videotaped student presentations, and examples of student work, to add detail to the chronology.

Once I had compiled the initial descriptive case, I began to incorporate interpretation of student decisions into a narrative case. I used several questions related to inquiry through design to help shape the narratives (see Table 3-2). These interpretations were meant to explain student decisions, and I drew on additional evidence to support or refute assertions about these explanations. Interpretations supported by evidence were incorporated into the narrative; disconfirming evidence led to the removal of unsupported assertions. The resulting narrative cases were the primary data source for my analyses of specific student inquiry.

It is important to note that these narrative cases are intended primarily to facilitate analysis of the work of the group and the group’s ability to pursue inquiry within a design context.
The cases are chiefly constructed by documenting group activity and the products of group design, and augmented by individual data such as student interviews or student written work. This approach is justified by the theoretical framework of inquiry through design, which encourages collaborative work and views knowledge as situated in the classroom, not the individual. My analyses of student inquiry thus represented the group’s ability to engage in inquiry and design.

However, it is also important to capture individual decisions, for group decisions are often resolved only after internal debate. Where possible, these cases identify and document internal debate as well as unanimous group decisions.

5.1.3 Mapping Design Practices to Inquiry

I argued in chapter 2 that elements of the iterative design process are analogous to steps in scientific inquiry. Inquiry through design is built around this idea of structuring the design process as a scientific investigation. To facilitate further analyses, I constructed a series of tables — one for each case — that are organized around central elements of the design process: design proposals, design decisions, design questions, design investigations, and resolutions that led to students accepting or rejecting the original proposal (see Figure 5.1). These elements all contribute to students’ ability to resolve design decisions.

![Diagram of Design Process]

*Figure 5.1. Elements of the iterative design process.*

*Design decisions* occur when students are presented with *design proposals*: ideas for incorporating certain materials or constructing a design in a certain way. Students must decide whether or not to accept the design proposal, based on what they know about the
idea, their own experience, and any relevant evidence available to them. In some cases, students may resolve the design decision right away, accepting or rejecting the design proposal based on what they already know. But often students may not know enough to be able to make an informed decision about the design idea. In these instances, design decisions lead to design questions.

Design questions reflect a need to learn more about the viability of specific design ideas. These questions could be framed as specific inquiries (e.g. *how will adding metal support rods improve my design*) or as more general investigations (e.g. *how does directional reinforcement affect the strength and flexibility of composite materials*). Design questions need not be pursued; in some cases, students may abandon the design proposal without fully resolving the design decision or may make an impulsive decision to accept or reject the design proposal.

Questions that are pursued lead to design investigations, where students plan and carry out some form of experiment to answer their design question. The results of these design investigations then serve to inform their design decisions.

The resulting design process tables document students’ design proposals, decisions, questions, and investigations as they progressed through the design project. Table 5.1 documents these elements from Sarah, John and Kathy’s design project. (Tables for the other classrooms can be found in Appendix D.)

These tables aid in identifying patterns within and across the observed groups. Because not all design proposals led to questions or investigations, some cells in the table are blank. Including these blank cells facilitated analyses that sought to understand why only a subset of design proposals led to design questions, or why only certain questions were investigated. These patterns served as initial assertions for the analyses that follow.
### TABLE 5.1.
DESIGN PROCESS ELEMENTS FROM SARAH, JOHN, AND KATHY

<table>
<thead>
<tr>
<th>Design Proposal</th>
<th>Design Question</th>
<th>Design Investigation</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day 1 (Design brainstorming)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kathy proposes using pipe cleaners.</td>
<td>How will pipe cleaners contribute to the design’s strength and stiffness? (P)</td>
<td>Planned five design variants, each of which used a different number of pipe cleaners. (C)</td>
<td>Not tested. Design idea initially accepted; proposal abandoned once telephone wire proposal was made.</td>
</tr>
<tr>
<td>Teacher suggests using tape; group quickly names several kinds of tape.</td>
<td></td>
<td></td>
<td>One kind of tape (duct tape) is used in students’ design.</td>
</tr>
<tr>
<td>Teacher reminds group of importance of bonding composite materials together;</td>
<td></td>
<td></td>
<td>Students use glue inside the straw to bond elements together.</td>
</tr>
<tr>
<td>Kathy proposes using glue.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Day 2 (Planning and building first set of design prototypes)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sarah proposes using telephone wire.</td>
<td>How does telephone wire contribute to the design’s strength and stiffness? (P)</td>
<td>Planned five design variants, each of which varied the amount of telephone wire. (C)</td>
<td>Tested. Results surprised the group and led to their redesign investigation.</td>
</tr>
<tr>
<td>Students propose slicing open the straws to make it easier to fit the wire inside them.</td>
<td></td>
<td></td>
<td>Students abandon the proposal once they find a way to insert material into the straw without having to slice it open.</td>
</tr>
<tr>
<td><strong>Day 3 (Testing)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Day 4 (Interpreting and presenting results)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Day 5 (Redesign of a set of design prototypes)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Students propose dissecting the telephone wire and using only the smaller wires inside the plastic sheath.</td>
<td>What parts of the telephone wire, the inside wires or the outside sheathing, contribute to strength and stiffness? (P)</td>
<td>Planned five design variants that varied the number of smaller inside wires to larger sheathing. (C)</td>
<td>Tested. Results surprised the group.</td>
</tr>
<tr>
<td>Teacher proposes that students explore materials that reinforce the outside of the straw.</td>
<td></td>
<td></td>
<td>Proposal rejected; students are focused on their own investigation of the wire.</td>
</tr>
</tbody>
</table>
5.1.4 Summary

The following four sections, 5.2 through 5.5, will describe specific analyses I used to describe and assess aspects of student inquiry: asking questions, planning investigations, reasoning using evidence, and pursuing explanatory goals. Each section will describe how the narrative cases and design process tables contributed to the analysis and what additional data was used to further test assertions about students’ ability to productively engage in inquiry. In section 5.6, I will discuss the implications of these findings in terms of the viability of design contexts for inquiry and the need for specific scaffolding to support student work.

5.2 Asking Questions: Relating Structure to Function

In chapter 1, I argued that students need support to effectively generate questions that they can investigate within the context of the classroom. These questions must be rich enough to sustain inquiry, but not so complex that students lack the time or resources to successfully investigate them.

Asking and pursuing questions about design performance is a central theme in inquiry through design that provides students with opportunities to generate questions for investigation. How well does this work? Are students able to generate their own questions that can lead to successful investigations?

In this section, I will describe and assess students’ ability to ask questions within a design context. First, I will review how students’ design questions were documented and assessed. Then I will characterize the nature of student questions and compare them to the kinds of questions that lead to productive investigation within inquiry through design. This will provide an overview and assessment of the kinds of questions that arise in inquiry through design settings. Third, I will address the sources of these questions. What aspects of the classroom context led students to generate these questions? To what extent is inquiry through design, the teacher, or some other element of practice responsible for supporting student questioning? Finally, I will discuss these results in terms of the contributions of inquiry through design.
5.2.1 Identifying and Assessing Students’ Design Questions

To identify students’ questions, I first drew on the design process tables that were distilled from the three narrative cases. These tables contain a series of design questions for each observed group. Each question was associated with the related design investigation, if any, that students pursued. These tables capture the issues the group discussed that relate to the design project and any questions that arose from these discussions. Note that for this analysis, all design questions generated by the group were considered, without regard for whether the group pursued the question. I then examined these questions and evaluated their suitability for later investigation.

Of course, students may have asked questions away from the group that were not captured by videotape or observed by the researcher. This approach does not claim to have recorded every question students ever asked. Instead, it attempts to show whether students are able to generate questions that can lead to productive inquiry. I believe my focus on the group is justified because the collaborative structure of the project implies that students are only able to investigate questions within the group. Questions that students ask outside of the group context either do not lead to investigation or must be introduced in the group discussion, at which point they would be documented in the narrative record.

Student design questions were evaluated based on their potential to lead to productive investigation within the design context. I reviewed student design questions with three goals in mind. While evidence that questions could support investigations was promising, better questions would relate structure to function, and even better questions would nominate specific causal structures and affected design functions. These three aspects of student questions are described below.

Could the question support a design investigation? We have seen that an issue facing student questioning is the ability to frame questions that can be productively investigated in the classroom. Such questions should not be so simple that students can answer them without investigation, nor so complex that they are beyond the resources of the classroom (Scardamalia & Bereiter, 1992). For example, student may ask questions about design materials that are not available for classroom use, or ask questions about an unrelated topic.
Did the question relate structure to function? I have argued that design contexts support explanations that relate structure to function. *Functional questions* seek to generate knowledge about this relationship. For example, students in Rachel’s class explored a question that sought to relate different reinforcing materials to the overall strength and stiffness of their design. This question is functional because it seeks to tie particular structural elements — the different materials — to design performance characteristics.

Functional questions are important in design settings because mapping structure to function — constructing an artifact to achieve a given result — is a main goal of design. Such questions relate to the scientific content of the activity. This goal can be seen in other design-based curricula that involve students in exploring structure/function relationships (Hmelo et al., 2000; Penner, Giles, Lehrer, & Schauble, 1996; Puntambekar, Nagel, Hübscher, Guzdial, & Kolodner, 1997; Sadler et al., 2000). Students who speculate about the relation of structure to function are proposing questions that not only lead to productive investigations within a design context, but also lead to a better understanding of structure to function relationships.

As a counterexample, consider a *nonfunctional* design question. Such a question explores an element of design that does not affect recognized dimensions of design performance. For example, a group might wonder how well their fishing pole flies, what materials would contribute to sustained flight, or what color would be the most pleasing to the eye. These may well make interesting projects, but hang time and color are not target properties of the fishing pole. Pursuing these questions will not lead to productive investigation of what makes a good fishing pole.

Did the question target a specific structure and function? Many functional design questions speculate about general performance. The earlier example from Rachel’s classroom demonstrates this: while the students have identified particular materials to investigate, they leave open exactly which design properties will be affected. These *speculative* questions can lead to productive investigation, but do not include specific predictions about design performance. The questions speculate about causal factors, but rely on empirical results to relate them to specific outcomes. They are more along the lines of “I wonder what this material will do to my design?”
A more productive question will target specific structural elements and functional properties. For example, in Doug’s classroom, one group sought to relate the ratio of coarse aggregate (pebbles) and fine aggregate (sand) in their concrete pot design to the rate of heat conduction. This specific question identifies a specific cause and effect and affords predictions that students can compare to later outcomes. Specific questions’ support for predictions suggests that such questions may lead to better inquiry because making predictions can help students to reflect on their results and make sense of evidence (Linn & Hsi, 2000).

5.2.2 The Nature of Student Design Questions

In this section, I will review the nature of student design questions and discuss whether students were able to generate questions that could lead to investigations, whether those questions were functional, and whether functional questions tended to be speculative or specific. I identified initial patterns of student questioning by reviewing the narrative cases for each observed group or groups. In some cases, I confirmed my findings by reviewing work from other groups in the classroom; I will cite this data where appropriate. However, only data from the narrative cases is detailed enough to document questions that arose during the design project; data from other groups is primarily limited to their final reports and presentations.

*Students generated questions suitable for investigation.* In each classroom, all groups engaged in design investigation, suggesting that students were able to pursue design questions. However, simply looking at the final products of students’ work does not tell us whether these questions arose from students or from other sources. We must look at evidence within the design project to make that assessment.

Within the groups profiled in the narrative cases, the evidence is positive. The group in Rachel’s class generated several design questions over the first day of design, including many questions prompted by their interest in using different materials. They continued to speculate about many design materials over the course of the design project.

Students in Lillian’s class were less prolific, focusing their initial question on the role of pipe cleaners and generating a new question about the role of telephone wire when Sarah forgot to bring pipe cleaners to class. In this case, it was unclear whether students had a genuine
question around the telephone wire idea. In a follow-up interview, Sarah describes the episode as motivated more from necessity than curiosity.

SARAH  This actually, this was kind of by mistake, although it turned out to the best. Um, we had originally talked about, um, pipe cleaners? But, I was supposed to go buy those, but I forgot, and so I brought this the morning of, and said well, you know, we could use this, and then we decided that it was a better thing because it would probably be more flexible and um, but sturdy and strong so that it wouldn’t just bend and crease. It would be flexible.

However, by the time this group began their redesign, it was clear that the surprising results from their initial tests had led them to explore the relation between structural elements of the telephone wire and functional properties of strength and stiffness.

Finally, students in Doug’s class also found interesting questions to explore. Many groups speculated about the effects of multiple design ideas, and tried to incorporate these ideas into their set of designs. For example, of the two groups profiled in the case, one group pursued two main questions, while the other managed to incorporate four design questions into their investigation.

*Student questions targeted functional properties of their designs.* Students in all three cases focused on functional questions throughout the design project. A review of the design questions that students raised in the three narrative cases shows that each of these questions focused on either overall design performance or a specific design property. For example, Lisa, Ellen and Carrie initially asked questions about how specific materials, used to reinforce the inside of their design, would improve overall performance. Later in the project, the group discovered that their design tended to fail because it wasn’t strong in a particular way: when the fishing pole was tested under a load, it bent and did not return to its original shape. This led the group to refine their focus, asking questions about whether specific materials would help solve their “bounce back” problem.

Why were students able to maintain a focus on functional attributes, rather than becoming distracted with other design attributes or even going completely off task? For one, the design goals were clear. Students were aware of the targeted design goals for the project
(e.g. strength and stiffness for the fishing pole) and their design questions were tied to these functional properties. In interviews following the project, students from each group were able to recall the main design goals for their project in terms of functional properties. This suggests that the framing of the design projects, which encouraged students to establish functional goals from the start, was successful. In the fishing pole projects, these goals were provided as part of the design challenge. In Doug’s classroom, where students proposed their own design challenges, Doug had each group identify core design goals prior to beginning to build designs.

Pursuing functional questions also meant that students were asking questions that related to the conceptual learning goals of the modules. The learning goals for each module were deliberately tied to the design properties and principles of the design challenge. In Composites, the goals include learning about tensile strength, compressive strength, stiffness, and the different means by which materials combine to form composites. In Concrete, the focus is on compressive strength, brittleness, and the different constituent materials — cement powder, water, coarse aggregate, and fine aggregate — that form concrete. If students were pursuing questions that related to target design properties, these questions would likely also relate to the stated learning goals.

For example, students observed in Lillian’s and Rachel’s classes investigated the structure of existing composites like telephone wire and explored different means by which multiple materials combine to form a composite, including directional reinforcement and bonding. Students observed in Doug’s classroom investigated the use of reinforcement (e.g. paper clips) to improve tensile strength and continually refined mix ratios to explore the role that cement, water and aggregate play in defining concrete’s properties.

One concern with students’ functional questions is that the questions focused predominately on design materials, rather than on how a scientific principle might help improve their design. When students focus on materials, what they learn about the material may not help them to evaluate other materials. This can promote a trial-and-error approach where many materials are tested but little predictive knowledge is gained. The staging activities in the Composites module were designed to address this concern by introducing different kinds of reinforcement and encouraging students to think about the importance of
general properties of composites, such as the importance of bonding constituent materials together to improve strength.

An example from Rachel’s class illustrates the risk of focusing on materials. After experimenting with a series of unrelated materials, Lisa, Ellen, and Carrie found that their testing results followed a similar pattern: the designs they tested typically failed by permanently deforming, much like a pipe cleaner will when bent. This led the group to search for a material that did not display this property. Although their tests led the students to narrow their search to a single design property, the tests provided no predictive cues to help them identify a material that would meet their need. Material selection was effectively trial-and-error.

*Students design questions tended to be speculative, not specific.* Although students were able to generate specific design questions, speculative questions dominated the design process, particularly at earlier stages of design.

Most documented student questions did not target specific design properties; rather, they speculated about the overall effect on the design. For example, in the case of Lois and Larry, the pair wondered “what would happen to the ball if there was a lot of sand in it.” As the narratives show, these kinds of questions lead to student investigations, but lack the specificity that would allow the group to make a precise prediction of what they think will happen. These questions tended to be broader and more focused on exploring new design ideas, although not yet exploring those ideas in enough depth to make specific claims about causal relationships.

In contrast, students in Lillian’s classroom, represented by Sarah, John, and Kathy, seemed to have the most success generating specific questions. This was due in large part to Lillian’s guidance. Lillian coached each group to make predictions that related their design idea to both strength and stiffness, in effect helping them to articulate their question to be more precise. Although students had time for brainstorming at the beginning of the project, they did not have access to design materials and they were encouraged to focus on picking a design variable rather than exploring a range of design ideas.

This coaching did not occur in the other classrooms, where specific questions were rare. Beth and Luke asked one such question that sought to relate the ratio of coarse and fine aggregate to the rate of heat conduction. The pair had learned in an earlier staging activity
how the aggregate ratio affected concrete’s strength and wanted to extend their understanding of this design factor to another design property. Beth and Luke’s second question, “what would happen if we used only water and cement”, was more speculative. The students weren’t sure which design properties might be affected, but believed that omitting all aggregate might improve the design in some way.

Lisa, Ellen, and Carrie also generated a couple of specific questions that focused on whether materials would improve their design’s strength. These questions came after they had begun testing and realized that strength was the property most important to their design’s performance.

The success of Lillian’s students in generating specific questions seems to derive primarily from her guidance; students did not generate such questions before her visits. This assertion is consistent with evidence from Rachel and Doug’s classrooms where tight guidance was not present and students more frequently asked speculative questions. Although students in Rachel and Doug’s classes did generate specific questions, this seemed to occur in instances where students had more knowledge of design results: staging activity evidence for Beth and Luke, and evidence from prior designs for Lisa, Ellen, and Carrie. The next section addresses the sources of students’ design questions in more detail.

5.2.3 Sources of Questions in Design Settings: What Prompts Student Inquiry?

We have seen that students are capable of generating functional questions. However, these questions are often speculative, and only in rare instances do we see students generating specific questions without substantial teacher guidance. What circumstances lead students to ask good questions? Here, I examine the elements of the design project that appear to spark student inquiry.

A review of the events that lead to design questions suggests that a range of events can spur student questioning, including the structure of the design project, surprising results that emerge from design testing, and controversial design proposals.

An initial spur in some cases was the structure of the design activity, which prompts students to generate a design question that they can investigate. Given this element of the curriculum, it is not surprising to find that students’ initial design questions arose from their initial claims about what would improve design performance. For example, during the
brainstorming phase of the design project, Lillian set an initial goal for students to identify a design variable that they would investigate by building a series of design variants. This meant that the design variable that the group selected would become their design question by default. After Sarah, John, and Kathy had decided to use telephone wire to reinforce their design, Lillian visited the group and helped them to refine their design question.

TEACHER What's your variable?

KATHY Um... number of... well before it was number of pipe cleaners, but we changed that.

TEACHER OK. So now what is it?

KATHY I guess, it's got to be something with the phone wires, I guess.

TEACHER OK. (pause)

JOHN 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? Number of wires that go through?

[...]

TEACHER So you're going to make five straws. Each of which has a different amount of wire inside. OK? So, which one's going to have... which one's going to be the strongest? (pause) Two goals, right? Strong and flexible?

JOHN Yeah.

ALL The bottom.

TEACHER The bottom? What, what do you mean, the bottom?

KATHY Like, the bottom straw, the first straw.

SARAH No, the...
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 (SARAH and KATHY) think too? OK.

By the end of this exchange, Lillian has helped the students to move from identifying a specific variable to articulating specific predictions relating that variable to two design properties: strength and flexibility. With her help, students have generated a design question that asks how the amount of telephone wire in the straw relates to both strength and stiffness.

The development of design questions through curricular structure was also apparent in Doug’s classroom, where students designed artifacts out of concrete. In his introduction to the design project, Doug encouraged students to try several different concrete formulations in addition to drawing on what they had learned in earlier staging activities. All four observed groups generated speculative questions about new formulations.

Surprise also triggered students to ask design questions. Often, new design questions emerged from students’ design experiences, because test results failed to meet student expectations or testing produced interesting results and side effects that students sought to explain. For example, the group in Lillian’s classroom began their design project without a strong investment in inquiry, choosing a variable (telephone wire) primarily to satisfy the demands of the assignment. But as John recounts during his group’s final presentation, their first test results surprised his group, largely because one particular design variant, the design that used two full lengths of telephone wire, turned out to be the strongest and the second most flexible of their designs. They had predicted that this design variant would be the least flexible of the five.
Throughout our project, our variable was the amount of wiring. At least in our first test we were going to use the amount of this kind of wiring... what we’d vary in each of our straws.

And in the first series of tests, we felt that — we put a different amount of this kind of wiring in each straw — and we felt that the middle straw, the one with... just one straw length of wire in the straw would be probably the best overall, most flexible and strongest. And then our other straws had two, two of these, two straw lengths; one and a half; the middle one, which was one; half length; and a quarter length. And we felt, once again, that the best one would be the middle one, since it... since the lower ones would have better flexibility and the higher ones would have better strength.

After testing with the spring scales on each of our straws, we figured out through test one that the best straw was the heaviest straw, which had two straw lengths of wiring. And this kind of shocked us because we thought it’d be a little... it would be too heavy and it would just be strength and wouldn’t be... flexible. But to our disbelief, it was, and it proved to be our best straw in our first series.

As a result, the group came to the redesign with a researchable question of their own: to explain how the different components of telephone wire contributed to the fishing pole’s strength and flexibility. Sarah explains later in the presentation.

In our second tests, we used these... the idea behind our second tests is that this part of the wire, the white part of the wire, gave it its strength, and the inside of the wire gave it its flexibility.

And so we decided to tear them apart, and in the first one we used only the smaller...
Some of the questions that students explored arose in response to controversial results or ideas. In these cases, disagreements among students led to design questions intended to resolve the controversy. For example, in Rachel’s class, Lisa, Ellen, and Carrie disagreed on the potential value of using modeling clay to reinforce their fishing pole design. Ellen proposed the idea, believing that the malleability of the clay would prevent the straw from crimping under load, which was one way their design could fail. She refused to abandon the idea despite Lisa and Carrie’s best efforts to convince her that the idea had no merit. Ultimately, Lisa agreed to help Ellen to build and test the design, responding to Ellen’s challenge to help produce empirical results to “prove her wrong.”

ELLEN Wouldn’t you like to prove me wrong?

LISA OK, we’re going to prove you wrong.

In this way what began as a disagreement over the predicted outcome of a design idea led to a specific design question and design investigation.

Controversy helped to shape other design questions as well. As they tried to make sense of their initial test results, Sarah and John disagreed on which components of telephone wire might be contributing to design performance. Sarah wanted to investigate the role of the four small wires within the main sheath (or wrapping). John wanted to evaluate the effect of the main sheath on their designs and compare designs with and without the wrapping. Here, the students argue about the design variants that they will build, starting with a single design containing the contents of two lengths of telephone wire.

JOHN This one has two [big] wires in them, without the wrapping?

SARAH So a total of four... (JOHN: Eight.) I mean eight... little things?

JOHN Yeah.

SARAH Oh, OK. Because I thought we were going to put in one like this [big wire], and then two little ones, and then the next one would have...

JOHN See, I don't think that would do it. Personally. I mean, I don't know... I think we should do some like that and then some with
just the little wires, and see what the difference is. You understand what I'm saying? I mean, could this... this one's...

SARAH So... just do it all... I just don't... wait. I just don't think it'll be as strong. I don't. (JOHN: Why?) Because this [the outer covering] adds a lot to... strength.

JOHN Oh yeah, the weight definitely gives it... yeah, but... I think... I don't know, I'd like to just see what one of these [thin wires] does as far as flexibility goes, because this could be extremely more flexible than one of these, don't you think?

The students continue to argue about their designs, and eventually compromise on a series of designs that will investigate the effects of both the small wires and the larger wrapping.

These example show how the structure of the design project, surprising results that emerge from design testing, and controversial ideas within groups can all lead to productive design questions. Of particular interest is the role of controversy, which has been used in other science curricula as a means to motivate students to engage in inquiry (Linn, Shear, Bell, & Slotta, 1999b). Intentionally incorporating controversy by introducing competing design ideas might spark students to engage in inquiry to resolve the debate.

5.2.4 Summary: Students Were Able to Generate Productive Design Questions

An important aspect of inquiry is asking productive questions that can lead to investigations. In this section, I have assessed the kinds of questions students ask in inquiry through design curricula and explored how inquiry through design leads to productive questions.

These results show that students were able to generate design questions that could lead to investigations. These questions were focused on the design goals of the project and successfully related design structure to function. With the exception of students who benefited from Lillian’s highly scaffolded guidance, students tended to ask speculative questions that did not tie design ideas to specific design properties. Instead, they focused on relating structural materials to general design performance. Aspects of the design project
that served to lead to productive student questions included the initial project structure, unexpected results, and controversial design ideas.

Of course, asking productive questions alone does not ensure successful inquiry. These questions create the potential to support effective investigation. Providing the scaffolding and support to help students success in engaging in scientific investigation is another matter. In the next section, I will explore the nature of student investigation within the design context and explain how students pursued the questions that they asked.

5.3 Characterizing Student Experimentation: How Do Students Pursue Design Investigations?

Generating good research questions is an important first step in scientific inquiry. As we have seen, students in ITD settings are able to propose a variety of productive research questions, some of which lead to investigations. In this section, we will explore the nature of those investigations.

Inquiry through design is intended to support student planning of investigations that generate comparative evidence suitable for evaluating scientific ideas. Students engage in multiple design investigations over the course the project. We saw in chapter 4 how students were able to plan, build, and test these designs in different ways. At issue is whether these investigations were structured to help students explain design performance. How well do students plan investigations to address the questions they raise? What kinds of support contribute to effective investigations — particularly comparative investigations — that disentangle the effects of competing design ideas?

My analysis focuses on instances in which students engaged in design investigation. These instances are documented in the narrative cases and summarized in Table 5.1 and Appendix D, and include formal and informal investigations, such as impromptu qualitative tests where students tried bending materials to gauge stiffness. I looked for patterns across time and across classrooms that would inform our understanding of how specific elements of inquiry through design contribute to student investigation.

I also evaluated the final reports and final presentations from all groups in each class. These artifacts provided additional examples of student investigation, since students were expected to document their main design investigations as part of their work. However,
these artifacts only documented students’ formal design investigations. Any informal or preliminary investigations that preceded these investigations were not captured.

I classified student investigations into two broad categories: exploratory and comparative investigations. Exploratory investigations were characterized by testing a single design or combining several design ideas into a single design variant. Lisa, Ellen, and Carrie engaged in exploratory investigation when they built one design, tested it, and then changed two aspects of the design before testing it again. These investigations typically focus on quickly assessing the performance of one or more design ideas. They have the potential to show that design ideas may improve design performance. However, these investigations lack comparative data and may bias students towards errors of false inclusion. Consequently, students may fail to understand the effects of several design ideas.

In contrast, comparative investigations are characterized by a set of design variants that assess the effect of a single design idea. Sarah, John and Kathy’s first investigation, in which they varied the amount of telephone wire used to reinforce their fishing pole, is an example of a comparative investigation. These investigations are intended to evaluate a single design idea by testing multiple variants to isolate the effect of the idea.

Ideally, students engaged in scientific inquiry will focus on planning and performing comparative investigations, because these investigations lead to comparative evidence that can support claims about the effectiveness of specific design proposals. Comparative investigation leads to evidence that supports claims about the effect of a single idea, although the interpretation of the evidence is still subject to reasoning errors like false inclusion.

I will draw on these analyses to review the nature of student investigation in terms of exploratory and comparative investigations, and discuss the relation of inquiry through design elements to student success planning and pursuing answers to design questions.

5.3.1 The Nature of Exploratory Investigations

Many students planned exploratory investigations. In Rachel’s class, Lisa, Ellen, and Carrie pursued several such investigations before coming in on their own time to plan a comparative one. Many students in this class actively experimented with new design ideas
before formal investigation. In Doug’s class, many pairs planned individual designs to explore a particular design idea. What led students to pursue these investigations?

Based on observational data, students’ exploratory investigations tended to reflect a desire to “see what would happen”: a phrase used by Lois and Larry to justify two of their five design variants. Many of these tests were rapid, informal experiments intended to learn enough to justify spending further time on the most promising ideas.

For example, students in Rachel’s class engaged in a variety of exploratory tests over the course of their design. One way that these students evaluated potential design materials was to pick them up and bend them to feel how strong and flexible the materials were. Lisa, Ellen, and Carrie used this approach to select design materials and to qualitatively evaluate their designs as they built them. Here, Lisa explains how she tested a series of potential design materials in a craft shop by bending them.

LISA  Well, I tried these plastic round things, and they were really really flexible, and I didn't think that would be good. Wood things, I thought would be ok, except sometimes when you bend them they start to splinter a little. I thought bamboo would be good, but I didn't get any. I didn't see any. But the thought came to mind. Let me think. Anything else? And there were these steel things. I didn't see how we'd cut them and plus they were a little bit too… they didn't move enough.

Exploratory investigations were not limited to qualitative tests. Students also designed exploratory tests that incorporated multiple design ideas. For example, students in Doug’s class planned exploratory investigations that included building a new design “to see what would happen to the ball if there was a lot of sand in it” (Lois and Larry) and designing two new variants because “we decided we didn’t want to do anything more with rocks or sand, so we made just two basic cement and water mixtures… just [to] see different mixtures” (Beth and Luke).

Lisa, Ellen and Carrie iteratively built and tested three different prototypes, using the results of each test to inform the design of the next prototype. This approach effectively provided the students with two redesign cycles over the course of the period. The group viewed this
exploratory iteration as “just testing” and modified two design factors in each iteration: removing some wires and adding fiber optic cable in the first iteration, and removing the plastic rod and swapping a wood skewer from the cable in the second.

Varying multiple factors in each iteration made it difficult for the students to understand how each design idea contributed to overall design performance. In a follow-up interview, Ellen admitted that her group could not identify which design ideas worked and which didn’t for this series of investigations. This confusion, exacerbated by the fact that the students did not document the results of these tests, led the group to plan and conduct a comparative investigation outside of class to make sense of the design ideas that they had explored (see section 4.3.3).

Exploratory investigations allowed students to pursue multiple new design ideas in an efficient manner. However, the results of these investigations served primarily to identify promising design ideas and did not provide evidence that allowed students to compare these design ideas to others. Such experimentation may have a place in the early stages of design, but when used in place of comparative investigations, as Ellen, Lisa, and Carrie did, exploratory investigations seemed to confuse students, who could not make sense of the results from these trials.

5.3.2 The Nature of Comparative Investigations

Comparative investigations were characterized by building a set of design variants that varied in only one way. Sarah, John, and Kathy’s investigations are representative of comparative investigations. In their first design iteration, the group built a series of designs that incorporated tape, glue, and lengths of telephone wires as reinforcing materials. The use of tape and glue was held constant over all designs; the only difference among the design variants was the amount of telephone wire.

Similarly, Lisa, Ellen, and Carrie were able to plan a comparative investigation to help them make sense of the conflicting results of their earlier exploratory investigations. This investigation allowed the students to compare the effects of using wire, wood, and a fiber optic cable to reinforce the center of one of three design variants. The results of this investigation supported student claims that fiber optic cables and wood were good reinforcing materials, as the design variants containing these materials substantially
outperformed the variant containing wire. Although they had begun to suspect wire during earlier exploratory testing, their data did not help them to reason about the role of wire because of the three designs they had tested, only one had contained wire, and the other two contained additional design materials not present in the wire design. This provided evidence to support the students’ belief that wire was not an effective material. The students carried the two effective design ideas into the final redesign, applying what they had learned to build a design that incorporated both fiber optic and wood and improved design performance.

Although both of these groups succeeded in performing comparative investigations, the classroom support for this kind of experimentation was very different. In Lillian’s class, the project was designed around two comparative investigations, and Lillian provided a great deal of direct support and coaching to help students plan their investigations. Rachel took a different approach, preferring to let students collaborate with other students in the class and plan their own investigations. A consequence of this approach was that the observed group floundered, spending most of their time in class exploring individual design ideas. While the group deserves credit for realizing the need to take a step back and engage in a comparative investigation, they had to do this on their own because they had run out of class time.

Students from each class engaged in the planning and execution of comparative investigations to better understand the effect of specific design ideas on design performance. Students in Lillian’s class, who had more direct coaching and scaffolding, were able to plan comparative investigations for both their initial design and the redesign. The group in Rachel’s class used a comparative investigation to resolve confusion over the effects of three design ideas that had been confounded in earlier exploratory tests.

Students in Doug’s class also engaged in comparative investigation. Doug provided coaching to help the groups to plan their investigations, which were modeled after those in an earlier staging activity. Interestingly, students in Doug’s class displayed a tendency to plan hybrid investigations that incorporated both exploratory and comparative elements. I will describe these investigations and explain the context that led to them in the next section.
5.3.3 Hybrid Investigations

Although students engaged in both exploratory and comparative investigation in Rachel’s classroom, they did so in a linear manner; they did not try to merge the two. An interesting aspect of investigation among the observed groups in Doug’s class was that students combined comparative investigations with additional exploratory tests that investigated completely different design ideas. The result was a mixed set of design variants, some of which related to each other, and some of which represented unrelated design ideas. This experimental approach of mixing comparative and exploratory investigations was problematic in some ways because students trying to make sense of their data often tried to draw generalizations that cut across all of their design variants, even those that represented different design ideas.

For example, Lois and Larry compared the effect of using paper clips to reinforce a concrete bocce ball. This experiment only required two design variants: one with paper clips, and one without. The students built three additional design variants to explore three unrelated design ideas: what would happen if a lot of sand were added; what would happen in only cement and water were used; and what would happen if they increased the amount of cement in one of their earlier designs. When the students tested their designs, they found that two of the exploratory designs performed the best overall. However, because these investigations was not structured to inform a comparative explanation for their success, the students had trouble pinpointing a particular design idea that could explain their results.

Focusing on the best designs also deflected attention from the original comparative investigation. The students’ conclusions focus on the stellar performance of these two designs without mentioning whether their two comparative designs taught them anything about the effect of the paper clips.

Students appeared to adopt this hybrid model of experimentation in order to explore a greater number of design ideas within a fixed period of time. Normally, exploratory investigations are an important part of the design process because they allow students to pursue new design ideas quickly. In Doug’s classroom, students had only one opportunity to build and test design ideas; unlike the other classrooms, there was no redesign phase. Compared to the Composites Module, a Concrete Module redesign is much more costly in terms of class time, because it concrete takes close to a week to cure. This means that
students cannot iterate on their designs nearly as quickly as in the fishing pole project, where students can test a design, build a new design, and test the new design within a single class period.

In addition to having no opportunity for redesign, students were not able to qualitatively test their materials as students did in the Composites Module because concrete must be mixed and must cure before its design properties may be evaluated. With no opportunity for rapid, qualitative screening or iterative design, students appropriated the formal design cycle as a means to explore new design ideas.

5.3.4 Summary: How Inquiry Through Design Shapes Student Investigation

Inquiry through design provides support to help students plan effective investigations, a major component of scientific inquiry. Regardless of whether it was exploratory, comparative, or hybrid, students in all three cases demonstrated that they were able to plan and conduct their own investigations of their own ideas. Students used the data from these investigations to reason about their designs. As a measure of engagement, this indicates that inquiry through design successfully encouraged students to pursue investigations on their own.

However, not all student investigations were as methodical as we would like. Although some students were able to engage in comparative investigations that explored the relationship between design structure and design function, students also frequently chose to engage in exploratory investigations that quickly tested many design ideas, but did not provide evidence that isolated the effects of specific design ideas. In some cases, the results from these exploratory studies interfered with students’ abilities to reason about the results of their comparative investigations.

Different aspects of inquiry through design contributed to this balance of exploratory and comparative investigation. For example, the hybrid investigations of students in Doug’s class may have been due to the lack of opportunity to engage in qualitative testing as well as the lack of an iterative redesign phase. This suggests not only that redesign opportunities are important, but also that certain content areas may be more suitable to inquiry through design. To reduce the desire of students to engage in hybrid investigations, inquiry through...
design may need to create more opportunities for early exploration, particularly within design contexts like Concrete that are less conducive to rapid qualitative testing.

Although student engagement in exploratory investigation did seem to interfere with students’ ability to make sense of their design ideas, this approach, when applied in the early stages of design, may help students to narrow the space of candidate design ideas. These investigations were useful for exploring the space of possible designs and often sparked student inquiry that led to the development of specific research questions. For example, although the sequential investigations performed by Lisa, Ellen, and Carrie did not yield comparable evidence, the investigations did help the students to identify the design ideas they would compare in a later investigation. However, these tests are less useful as supporting evidence for student explanations of design performance, because the results are often not quantifiable (and in the case of this group, not documented).

Screening strategies may in fact be an important precursor to inquiry. This informal exploration often uncovers surprising or controversial design ideas that students later explore in more detail. Within both the engineering community and the scientific community, exploratory investigations as a form of screening are an accepted approach to winnowing down a large space of design ideas (Beveridge, 1950; Bucciarelli, 1994). However, the relationship between this form of investigation and more formal comparative testing needs to be well defined.

Inquiry through design provides time for verbal screening during design brainstorming, but does not encourage students to test materials qualitatively. Students created time for screening later in the design process, especially in Rachel’s class, where the nature of the materials — plastic, wood and wire — lent themselves well to rapid qualitative evaluation. This suggests that inquiry through design may need to make these models of investigation explicit and may need to encourage students to engage in the iterative refinement of not only their designs, but also their experimental methods, over the course of multiple design iterations. Studying how the exploratory nature of early design can contribute to student inquiry will help to refine inquiry through design to provide greater synergy between these two fields.

These findings illustrate an important tension between engineering design goals and inquiry goals. Engineering goals that center on improving design performance are often
served by rapidly exploring multiple design ideas. Inquiry, which centers on understanding the effect of specific design factors, often benefits from a more measured, comparative approach to investigation. Providing opportunities for iterative redesign can address this tension in different ways: by distributing the goals across design cycles, or by allowing students to engage in iterative refinement over time. For example, the group in Rachel’s class used their first design cycle to explore several different design ideas, and their later redesign to construct a comparative investigation based on earlier results. The group in Lillian’s class engaged in comparative investigation during both design and redesign, but their redesign allowed them to explore the role of a specific design factor in greater detail. A goal for future work is to explore possible models for integrating inquiry and design goals through iterative refinement. A further challenge for curriculum designers is to devise ways to support iteration when the domain content is not particularly amenable to rapid design cycles, as was the case with concrete.

5.4 Reasoning With Empirical Evidence

Well planned investigations can produce evidence that helps students to disentangle the effects of different design ideas. To reap the benefits of inquiry, however, students must be reason about evidence in order to make claims that will stand up to argument. Inquiry through design addresses this need by helping students to generate evidence about their designs and providing structured opportunities to use evidence to make and justify design decisions. Here, we turn our attention to how students used evidence from multiple sources —staging activities, their own design results, and other group’s design results — to reason about design ideas.

Students make design decisions, based on a range of available evidence, over the course of the project. In addition to data from their own investigations, student can draw on the results of other groups, the results of earlier staging activities, and the suggestions of peers and teachers. In order to understand how students use evidence to reason about their designs, I will examine the nature of evidence available for student reasoning and the ways students used evidence to support their design decisions.

The focus of this analysis are the design decisions identified in the narrative cases and summarized in Table 5.1 and Appendix D. These decisions include instances where students
considered new design ideas from sources that included the group, other groups, and the
teacher; instances where students presented and defended their design results to others; and
students’ final explanations of design performance. In each case, I sought to document the
nature of evidence available to students and assess the degree to which students drew on
this evidence to inform their design or support their claim.

Students’ ability to reason about empirical evidence is naturally constrained by the quality
and quantity of evidence available to them. One argument for why design affords inquiry is
that empirical results provide evidence to support student reasoning. Therefore, I will first
discuss the nature of available evidence in the design setting. Once the nature of available
evidence has been established, I will move on to discuss the nature of student reasoning
using this evidence.

Student success reasoning about design evidence is shaped in part by the kinds of support
for reasoning that exist in the classroom. Finally, I will describe how aspects of inquiry
through design support or detract from the use of evidence to support student reasoning.

5.4.1 The Nature of Available Evidence

As students build and test designs, they naturally accumulate evidence in the form of test
results. This process begins during the staging activities, which are intended to provide
experimental evidence and scientific principles that may be applied during the design
project.

The available evidence from staging activities varied in each classroom, and was influenced
by the way the teacher structured these activities. In Lillian’s classroom, students spent little
time on staging activities and generated only qualitative evidence about the strength and
stiffness of reinforced foam beams. Lillian had students flex the different designs by hand to
assess the difference in strength and stiffness.

In Rachel’s class, students spent more time on this activity and tested the different beams
more precisely, using a formal testing apparatus to produce quantitative data for strength
and stiffness. Students in Rachel’s classroom also generated data about the effectiveness of
different kinds of directional reinforcement on strength and flexibility.
Students in Doug’s classroom generated comparative data about the effectiveness of different ratios of cement, water, and aggregate in the design of concrete and documented their results on large pieces of butcher-block paper. Doug hung these posters in the back of the room so that the data would be available to students during the design project.

In addition to the staging activities, students generated data as they built and tested various designs. This meant that students had access to data from their own tests as well as that of other groups. Rachel’s class in particular saw substantial exchanges of design ideas among groups. Rachel openly encouraged this practice of building on each other’s work and prompted students to share their findings by contributing to a table on the blackboard that summarized whether specific design ideas resulted in improved designs. In fact, Lisa, Ellen, and Carrie planned to capitalize on this sharing of design ideas by focusing their efforts on one aspect of the design and learning about other design ideas from other students.

ELLEN Yeah, you know what else we could do though? Is we could just test the inside, and just decide that this is the outside that we like, because they’re [other students in the class] going to tell us about outsides tomorrow.

Although students had access to data about a variety of design ideas and design principles, not all data was suitable for supporting specific design decisions. While the staging activities were intended to produce evidence that invited comparison, the evidence that students generated during the design process reflected the range of investigations that students pursued. This included the results of exploratory testing, such as Lisa’s informal testing of materials at the craft store, as well as the results of more carefully planned comparative tests, such as Beth and Luke’s investigation of the effect of varying ratios of aggregate on heat conduction. Consequently, many of the results of exploratory tests were not directly comparable, because so many materials varied across the different designs.

A prime example was the range of conflicting reports surrounding the use of wood in Rachel’s classroom. When Lisa, Ellen, and Carrie faced a decision about whether or not to use wood in their design, they had to reconcile one student’s report that wet bamboo worked well, a note on the blackboard from another group that claimed that wet wood did not work well, and Rachel’s own suggestion that wood skewers were a good bet.
The ability of design projects to generate evidence is clearly a two-edged sword. As we have seen, students were able to engage in comparative investigations, and these investigations often led to useful data. But students were also faced with a wealth of exploratory evidence that resulted from the numerous informal tests they used to evaluate promising design ideas.

Students in these classrooms had varying access to a broad range of data. Results from past staging activities were available in students’ lab books or, in Doug’s class, on a poster on the wall. Results from the students’ own design testing were documented in the students’ own design log — unless they decided not to write anything down — and present in students’ memory of the test results. Results from other groups’ design tests were also available, and usually presented verbally, through suggestions or formal presentations. In less formal settings, results from other groups were usually communicated only through a recommendation to use or avoid a specific material (e.g. “fiber optic cables don’t work”). Students did not have direct access to the empirical design results from other groups.

Students faced the challenge of sifting through this range of data and identifying evidence relevant to their design. In the next section, I will discuss students’ ability to make sense of this data to inform their design decisions.

5.4.2 How Evidence From Staging Activities Informed Design Decisions

Student use of evidence from staging activities varied in each classroom. The use of evidence from staging activities to inform design decisions was most pronounced in Doug’s class, where most groups based their design’s formulation on the results of an earlier activity.

For example, Lois and Larry decided to design lawn bowling (bocce) balls out of concrete. The two main properties they chose to test were strength, measured by the ability to withstand being dropped from a height, and uniformity of the surface, so the ball would roll well. In earlier staging activities, the class had tested a wide range of concrete formulations to determine their effect on strength and brittleness. Since Lois and Larry were testing for a similar property, they justified their initial designs by writing that “the first 2 samples were the same measurements as the 2 strongest concretes from the previous reinforcement project.”
Beth and Luke took a similar approach, using the results of the earlier activities as a starting point for their investigation. They decided to design concrete cooking pots, and chose to focus on the rate of heat conduction as their main design property. Previous staging activities had primarily focused on strength and brittleness, not heat conduction, and the group acknowledged in their design journal that “we haven’t done anything in the past concerning heat. Our experiments rely completely on heat conduction so we really have no idea how the mixtures will react.” However, the students inferred a more general principle from the earlier activity, justifying their choice of mix ratios by stating that “in all of our past experiences, mixtures of coarse and fine [aggregate] have performed best.”

By contrast, the groups in Lillian and Rachel’s classes rarely drew on the results of earlier activities during the design project. For example, an important finding in one staging activity was that composite materials whose constituent materials were not bonded together were much weaker than composites that were bonded. The intended implication for the design project was that students should bond their design materials together to increase design strength. In an early interaction with the group, Lillian reminds them of these earlier results.

LILLIAN  OK, 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 cleaners stuck to the straw?

KATHY  Glue.

LILLIAN  OK. Then that would be a material that you use.

A day later, Lillian returns to the group. At this point, the group has decided to use different materials, replacing pipe cleaners with lengths of telephone wire. During the process of changing design ideas, Kathy’s idea about using glue has been forgotten. Lillian again prompts them about the importance of bonding materials together.

TEACHER  OK. How are you going to bond the wire to the straw?

SARAH  (pause) Must we?

TEACHER  Yes.

SARAH  OK. Um... we could put... glue?
Sarah’s resistance to the suggestion to bond the wire to the straw implies that a principle the staging activity was intended to convey — that bonding directly affects strength and stiffness — was not applied. This suggests that either the staging activity did not succeed in conveying the principle, or that Sarah and her group were unable to transfer the principle from the foam beam context to that of their fishing pole. In either case, this implies that this staging activity did not fulfill its goal of informing later design efforts.

This was the only instance during the design project in which the group considered how the results of the earlier activities might inform their own design. Had Lillian not prompted the group, they might not have considered the role of bonding at all.

The group in Rachel’s classroom similarly drew on staging activity evidence only once to inform their design, although it did not require a prompt. Earlier, the group had investigated the effect of directional reinforcement by wrapping fiber-reinforced tape around a Styrofoam beam at different angles and exploring which angle best increased the stiffness of the design. The results had indicated that orienting the fibers longitudinally (the “long way”) led to the greatest improvement in stiffness.

Ellen capitalized on that result during the design planning phase of the project and suggested the use of another kind of fiber-reinforced tape, duct tape, to strengthen their fishing pole. Here, she shows that she remembered the general principle from the geometric reinforcement activity: that the direction of reinforcement affects strength.

ELLEN  Well, you know what we should put on the outside is duct tape.

[Gestures like pulling a thread] It has threads in it, like that [activity] did. If you put it the long way it won’t bend as easily.

Ellen recognized that duct tape contains embedded threads that were similar to those found in strapping tape. She applied the findings from that activity — that orienting the reinforcing fibers along the axis of tensile stress improved the composite’s strength and stiffness — to a new context. In this case, results from a staging activity were used to inform design.

Why were staging activity results adopted more frequently in Doug’s class than the others? My analysis suggests two factors that contribute to this difference. First, in Doug’s classroom, the data was directly applicable to the students’ design. Although each group chose its own object to design, most decided to base the performance of their design on
either strength or brittleness, two factors that they tested in the earlier activity. Since the materials and the desired properties matched, the value of the earlier results was obvious.

The Composite staging activities, unlike the Concrete activities, did not involve the same materials as the later design project. These activities involved building composites of foam and paper, but these composites did not look like a fishing pole and students did not generalize their findings in order to apply them to the design project. In the one case where Ellen did apply the findings of the earlier activity, she was using a material (duct tape) that was very similar to the earlier material (strapping tape).

Teacher prompting also played a role in two classrooms. Doug actively encouraged students to draw on evidence from the earlier activity and posted these results on large sheets of paper that were hung in the back of the room where students could easily refer to them. Lillian specifically prompted the group to consider the effect of the earlier activity and how it related to their design work.

Students appeared to use evidence from staging activities to support their reasoning about design in limited instances. The most successful instances occurred when there was a strong similarity between the materials tested in the staging activity and the materials used in the design. For example, students in Rachel’s class were able to analogize from the fiber-reinforced strapping tape of the geometric reinforcement activity to the fibers in the duct tape that they used to reinforce their design. Similarly, students in Doug’s class all drew on earlier test results from the reinforcement staging activity. Here, students were designing new objects from concrete, and the earlier results that addressed the strength and brittleness of various concrete formulations were clearly relevant.

The difficulty relating the results of staging activities to later design decisions may be in part a problem of recall. Students may need more support to make these results more accessible. Doug’s success posting the results of earlier staging activities suggests that making evidence more accessible may indeed contribute to student inquiry. However, this approach needs to be studied in other settings, because students may also have drawn on these results simply because they were so obviously applicable.
5.4.3 How Experimental Evidence Informed Design Decisions

In addition to using staging activities to support student reasoning, inquiry through design also relies on the process of building and testing designs to generate useful empirical evidence to inform students reasoning about the relation of structure to function. The empirical evidence that results from design testing is a key affordance of design contexts for supporting this challenging aspect of inquiry.

Experimental evidence played several roles in students’ design decisions. Most importantly, these design results provided the means for students to evaluate their design ideas. These opportunities were mostly centered in Lillian and Rachel’s classrooms; Doug’s class did not have time to participate in a redesign phase, which is the primary opportunity to apply earlier design results. The main challenge facing students was whether they could discriminate among the variety of available evidence and base their design decisions on comparative data.

One important characteristic of the experimental evidence was that evidence that emerged from testing sometimes led students to investigate new design ideas. The fact that students found the results surprising contributed to their engagement in inquiry. For example, Sarah, John, and Kathy responded to the surprising results of their initial tests by investigating a new relationship between the outer covering of the telephone wire and the strength and stiffness of the design. The group began their design with a simple assumption, shown in their initial predictions, about how telephone wire would relate to strength and stiffness. They predicted that the design with the more wire would be the strongest, and the design with the least wire the most flexible. As John and Sarah stated in the group’s presentation, the results of their design testing surprised them and prompted them to investigate more closely the elements of the wire in order to understand how these elements contributed to design performance.

The evidence that the students generated led them to reflect upon — and revise — their understanding of how the structural components of their design (telephone wire) contributed to the design’s functional performance (strength and stiffness). Engaging in this kind of reasoning, in which existing explanations are tested against data and alternative explanations are generated to attempt to make sense of the data, is a key component of scientific inquiry. The explanations the students presented that were supported by existing
evidence indicate that the students were actively engaged in making sense of the data they gathered.

Students reasoned about their designs using evidence gathered from both exploratory and comparative investigations. Evidence from exploratory cases proved challenging for students to interpret because these results were generally not directly comparable. For example, Lisa, Ellen, and Carrie could not resolve the results of their three initial design prototypes, because design ideas overlapped across the designs. Similarly, students in Doug’s class were faced with the challenge of making sense of the results from five design variants, only two or three of which were directly comparable. This led to some errors in analysis, such as Beth and Luke claiming that the rate of heat conduction was related to the amount of water in each design. Although the amount of water was greater in the two designs that took longer to boil, the results could also have been explained by claiming that these two designs were the only two that did not contain aggregate. The absence of comparable designs, due in this case to the addition of two exploratory designs, prevented students to making valid claims about their results.

Although students’ reasoning about their own design ideas was generally based on the available evidence, students tended to accept claims of other groups without considering whether supporting evidence existed. For example, Lisa, Ellen, and Carrie often relied on evidence to resolve their own competing ideas. However, when the group was presented with the results of another group, the students accepted these results without requiring supporting evidence. For example, the students accepted another student’s claim that fiber optic cables “didn’t work,” even though their own testing had shown that, compared to other design materials, fiber optic was quite effective.

Another example was the students’ decisions surrounding the use of wood as a design material. Prompted by another group, Lisa began to incorporate wood into a design. When Carrie saw that wood was listed as a material that didn’t work, Lisa abandoned the design. Later, Rachel suggested that wood was a good material after all. In each of these cases, group members accepted conclusions absent confirming evidence, even though the results were often in direct conflict with what they had learned earlier. Two factors may have contributed to this. Interviews with Rachel suggest that the girls in this group were not very self-confident about their work, and they may have assumed that results in conflict with
their own meant that they had done something wrong. Alternatively, the group may have presumed that these claims were supported by evidence, and simply didn’t bother double-checking. In either case, this suggests that students need specific support for sharing and critiquing arguments between groups, including the modeling of critical analyses of scientific claims.

Another concern is that the nature of student explanations was somewhat shallow. Students’ conclusions, as evidenced by their final reports, used data to support claims that related structure to function. For example, Ellen reported that fiber optic wire was an outstanding material for improving design performance: a claim supported by her comparative data. However, students also sought to explain the role of other design elements, even when the data did not support such claims. For example, Ellen also wrote that duct tape increased design flexibility, even through duct tape was included in all designs and she lacked comparative data to support this claim. Further, this claim runs contrary to Ellen’s original insight that the geometric orientation of the fibers in duct tape improve the stiffness of the design. It was not clear that Ellen distinguished among explanations that were evidence-based and explanations that were not.

5.4.4 Summary: Student Use of Evidence to Reason About Design Decisions

How did aspects of inquiry through design contribute to student reasoning? Without a doubt, the process of building and testing designs generated a wide range of evidence in the form of design results. In many cases, these results proved surprising to students and led to new investigations or refinements of previous investigations as students sought to explain why their designs performed as they did.

We have seen that students draw on evidence, primarily from their own prior design testing, to inform and improve their designs. In certain instances, students considered evidence generated in earlier staging activities, but this only happened when there was a high degree of similarity between the materials used in the activity and the materials being used in design or when the teacher took specific steps to make this evidence available to students.

These results suggest that while students were able to use evidence to inform and improve their designs, greater scaffolding during staging activities may help students construct
generalizations that they can apply to the later design project. Although each staging activity has at least one reflective question intended to prompt students to relate what they learn to a design context, these questions may not be explicit enough. Likewise, stronger scaffolding during the design project that encourages students to revisit earlier work may lead to better use of evidence to inform design ideas. Such scaffolding is especially needed where staging activities lack obvious surface similarities to the materials in the design challenge.

Student use of experimental evidence occurred, but was not as strong as had been hoped. This was largely due to students’ persistence in planning exploratory investigations that produced data that could not be easily compared to other design results. Students in at least one class also used different standards to evaluate different design claims. Although they relied on empirical data for group testing, they adopted many design ideas from other groups without checking to see if any data supported those claims. This suggests that students may need additional scaffolding to use evidence effectively to make decisions about design ideas.

One aspect of students’ explanations that could have been improved was that they did not suggest a causal mechanism for the relationships they posed. Student explanations were primarily limited to asserting the relation between structure and function and did not go further to explain why a particular structural element affected design performance as it did. However, the fact that students successfully identified these relationships is an important first step towards constructing more complete explanations of design performance.

In fact, the nature of the evidence that students gathered may not support deep conceptual explanations. Although students can empirically demonstrate that a fishing pole made of wood is more flexible than one made of steel, explaining the causal mechanism behind this relationship (e.g. why wood is more flexible than steel) requires deep conceptual understanding. In materials science, many of the deep causal explanations for material properties depend on understanding the materials at a molecular level, a depth of analysis that goes beyond the scope of these design projects. Instead, students are limited to explanations that identify the relative effectiveness of different materials and construction techniques, but cannot explain the fundamental differences in material properties. This
suggests that another factor to consider when crafting inquiry through design challenges is the extent to which students can develop causal explanations within the design domain.

5.5 Balancing Explanatory and Performance Goals

The preceding analyses have focused primarily on specific components of the inquiry process: asking questions, planning investigations, and reasoning using evidence. In this section, I will focus on an overarching aspect of engaging in inquiry that cuts across these multiple components.

Inquiry is driven by the goal of explanation: to be able to explain why particular phenomena in the world happen. In this section, I will discuss how student engagement in inquiry through design related to their adoption of explanatory goals. Within the design context, these goals are reflected in student investigation of why certain design ideas affect design properties as they do.

In chapters 1 and 2, I raised the concern that students placed in a design setting may focus solely on meeting or exceeding the design goals rather than conducting investigations that help them explain relationships between structure and function. Past research has shown this concern to be real (Roth, 1996; Sadler et al., 2000; Schaub et al., 1991b).

But simply having a design performance goal does not by itself implicate design as a poor context for inquiry. Performance goals only become an issue when they interfere with students’ ability to pursue explanatory goals. The inquiry through design approach acknowledges design goals and tries to structure the design task like a scientific investigation in order to support the pursuit of explanatory goals as well.

In this analysis, I will explore the balance between design and explanatory goals and the conditions that seemed to foster student adoption of one the other. To examine how students pursued design and explanatory goals, I will discuss students’ own perceptions of the design project, as captured on videotape and in follow-up interviews, and also synthesize results we have seen concerning student questioning, planning, and reasoning. The pursuit of design goals is characterized by a stated focus on improving performance and the investigation of multiple design ideas in order to identify effective ideas quickly. Explanatory goals are characterized by a stated focus on learning or explanation, coupled with careful investigation of specific design ideas to isolate their effect.
5.5.1 Design Goals Dominated Student Investigations

To assess students’ perceptions of the purpose of the design project, follow-up student interviews included two questions that asked students to explain how important design performance was over the course of the project and how important it was to be able to explain why their design worked.

Students consistently reported that over the course of the project, design performance was an important goal of their work. Here, Lisa describes how she felt about performance. While she disagrees that the group felt it was important to have the best design in the class, she also states that the group “wanted to build a design that worked well.”

Interviewer So while you guys were building these designs, how important was it to you that you were trying to build the best design possible?

LISA I don't know. In the end, it wasn't as important, because we knew our design wouldn't work. When we were first trying it I think it was more important. I'm not sure we were just striving to go for the best design, but we were trying to make a design that we thought would be good but not necessarily... I don't think we were necessarily thinking oh mine has to be better than yours. It was just like... we wanted to build a design that worked well.

Ellen’s view concurs with Lisa’s. She also felt that while competition wasn’t a driving force, producing a good design was important. Her comments reflect the group’s interest in seeing their good design ideas succeed.

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. So, yeah, we tried to do the best...

Other groups were even more performance oriented. For example, a group of three boys shared a lab table with Lisa, Ellen, and Carrie. All three stated in interviews that their goal for the project was to win the design challenge. (They did.)

Evidence from the narrative cases also suggests that students made decisions to improve performance in more cases than to generate investigations. We have already seen how students adopted exploratory approaches to investigation, either through rapid iteration in Rachel’s class or hybrid experimentation in Doug’s class. Only in Lillian’s class, where student work was highly scaffolded, did students conduct comparative investigations from the start. But even here, Sarah and John both viewed the main goal of the design project as building, as Sarah put it, “the ultimate fishing pole.”

It’s not surprising that students adopted design performance goals for the project; after all, the design challenge is just that: a challenge to create an effective design to meet a goal. What was more surprising was that students were less consistent in stating that their work during the design project was driven by a need for explanation.

In Rachel’s class, both Ellen and Lisa agreed that explanation was important. To Lisa, evaluating why her group’s designs did or did not work was a central part of what they did.

Interviewer How about being able to explain why it was that your design worked. Was that something that you were aware of trying to do while you were building them?

Lisa Yeah, I think we were trying to evaluate why our design did or didn’t work in certain aspects, and everything. I think we were trying to do that all along. And we were trying to think of ways that it could be improved. Everything like that, so...

However, other students were less convinced. Carrie flatly denied that explanation was a goal, as did the three boys in the other lab group. Evidence from students’ investigations supports this view: we have already seen that, absent strong scaffolding, students tended to engage in exploratory investigation that allowed them to explore multiple design ideas.
Students’ ambivalence towards explanation goals is particularly interesting in light of their understanding of the assessment measures used in each classroom. When asked what they thought their teacher was looking for when grading their projects, students made it clear that performance was not a factor in their grade. Their responses are consistent with the actual rubrics used; none of the three rubrics used by Lillian, Rachel, or Doug valued design performance at all. The only instance in which performance impacted assessment was when Rachel offered extra credit points to the group with the best design. (I will discuss teachers’ use of assessment to support inquiry through design in more detail in chapter 6.)

Why did students persist in pursuing design goals when they knew that their grades would not reflect design performance? This is in part testament to the tremendous motivation of authentic design challenges. Design may have been too successful at providing a compelling problem-solving environment. But it also indicates that students may need to be reminded of explanatory goals over the course of the project, or have scaffolds within the project to highlight explanation. The presentations in Lillian’s class, where students explained what their design was and why they thought it would do well, may be an example of the kind of support that helps address this issue.

5.5.2 Design Goals Were Reflected in Extended Exploratory Investigation

Students’ focus on design goals is reflected in a broader pattern of practice that relates students’ design questions and the investigations that derive from these questions, and ultimately contributes to difficulties reasoning about design evidence in a systematic way.

Inquiry through design structures design investigation so that students explore relations between structure and function. We have seen in section 5.2 that in this respect, students were successfully asking questions that seek to tie design materials to design performance. However, we also saw in section 5.3 that students often pursue exploratory investigations. As a result, students are generating data that do not afford comparative analysis, and leave students, as Lisa put it, unsure if they “really knew what did work and what didn’t work.” Why did these questions frequently lead to exploratory investigations, rather than comparative ones?

The narrative cases suggest that the goals that students held when planning the investigation determined whether they shaped exploratory or comparative tests. Students
were more focused on seeing “what would happen” and whether new design ideas would improve their design. This approach led students to defer, or ignore, explanatory goals.

For example, Lisa, Ellen, and Carrie built and tested a series of designs in class. At one point, their previous design, which used metal wires, was not successful, and they went looking for other materials to replace the wires and reinforce the inside of their design. Lisa proposed using a length of fiber optic cable. However, rather than replacing all of the metal wires, the students kept about half to use with the cable, arguing that they were needed to fill empty space inside the straw and provide better support. That meant that they had varied two things from their previous design: the number of wires and the fiber optic cable. The students were aware that they had just added a second variable, but dismissed it on the grounds that they were still “just testing” different design ideas, and had not begun building their three official prototypes.

   LISA  We can’t use another variable.

   CARRIE  Can we use duct tape?

   LISA  Yeah...

   CARRIE  Well we’re just testing, we’re not making our three with one variable, are we?

   LISA  Yeah, I guess not...

This example shows that these students were aware of the goal of building comparative designs when they planned their next investigation, yet they chose a more explanatory approach anyway, in part because doing so meant building a design that they felt would perform better. As we saw in chapter 4, this decision was one of several that contributed to this group’s later difficulties explaining which design ideas worked and which did not.

A similar problem arose with the results of hybrid investigations conducted in Doug’s class. Here, students proposed two or three comparative design variants, but also chose to include a few unique designs just to see what would happen. For some students like Lois and Larry, once they tested their designs, they found that their exploratory variants had outperformed their comparative ones. In Lois and Larry’s case, this led them to focus their lab report on trying to explain why their best design did so well. This was a difficult task given that this
was an exploratory investigation and the students did not have enough evidence to identify a causal design idea. More troubling, the students’ focus on explaining the best idea meant that they did not bother to discuss the results of the comparative investigation that Larry planned to prove whether paper clips made good reinforcing materials. The students’ focus on only the best design meant that they missed an opportunity to learn about an important design idea.

These examples demonstrate that students’ interest in producing outstanding designs can bias them to engage in exploratory investigations and ignore comparative design evidence. This points to the need to provide greater support for explanation, particularly at moments when students begin to plan investigations.

5.5.3 Explanatory Goals Arose in Response to Empirical Discoveries

In spite of a tendency to focus on design performance goals, students did pursue explanations in selected instances, planning comparative investigations and turning their attention toward understanding a particular relationship between structure and function.

For example, we saw Sarah, John, and Kelly choose to pursue a better understanding of the role of the constituent materials in telephone wire as a result of surprising test results. Lisa, Ellen, and Carrie argued over the potential effect of modeling clay on their design and planned an investigation to resolve the controversy. This group’s confusion of their initial design results, combined with an awareness that they needed to plan a comparative investigation as part of the project requirements, also led them to investigate more carefully the contributions of three specific reinforcing materials. In Doug’s class, Beth and Luke planned a comparative investigation to extend the results of a staging activity to a new design property. Lois and Larry built two designs to compare the effect of a questionable reinforcing material first studied in an earlier staging activity.

These examples illustrate a wide range of events and rationale for pursuing more explanatory investigations, yet share a common source. Each arose from student interest in an empirical result: students’ own design testing, earlier staging activity results, or other students’ design results. This suggests that in at least one respect, the evidence that emerges from design contexts does support student inquiry. This also suggests that an initial exploratory phase, during which students might generate surprising or controversial
results, may lead students to pursue personally relevant explanations for design performance.

Clearly, we would like to see students pursuing explanatory goals with more consistency. Building support for such explanatory “triggers” will require a better understanding of the nature of design events that spark student interest in pursuing explanatory goals.

5.5.4 Summary: Negotiating the Balance Between Science and Design

Students engaging in design projects must negotiate two sets of project goals. Design goals intrinsic to the design challenge encourage students to pursue design ideas and to improve design performance. We have seen that students readily adopt these goals, and sustain them over the course of the project. In this respect, these results are similar to those seen by other researchers using design as context for science learning (Hmelo et al., 2000).

However, to successfully engage in inquiry, students must also adopt explanatory goals. Within the design context, these goals focus on understanding how design ideas relate to design performance. We have seen that students ask questions and plan investigations that target relationships between design structure and function, but frequently these investigations stop short of pursuing causal explanations and are content to demonstrate the presence of a relationship. Often, the investigations that students plan to pursue these relationships fail to generate comparative evidence to convince others of the value of the design.

Design, and the exploratory investigation that may accompany it, do serve to engage students in the task. Even within a scientific investigation, rapid exploration plays a role (Beveridge, 1950). However, students may need more explicit support to make the transition from focusing on improving design performance to focusing on refining explanations for that performance.

One potential approach may be to scaffold design in more explicit stages. For example, the design task might be split into an exploratory stage and an explanatory stage, where students first freely explore a range of design ideas and then examine the more promising ideas to determine how these elements contribute to design properties. Hmelo and Kolodner describe a similar approach, which they term “messing about”, in which students
explore a variety of design ideas before having commit to a specific course of action (Hmelo et al., 2000; Kolodner et al., 1998).

This approach is consistent with Schauble’s argument that moving students from an engineering framework to a scientific one is more productive than beginning in a scientific framework, because initially students may not value the comparative methodologies that inquiry employs (Schauble et al., 1991b). This approach also builds on characteristics of anchored instruction that date back to Dewey, and hold that students are more likely to want to understand phenomena that help them to generate particular outcomes (Bransford, Sherwood, Hasselbring, Kinzer, & Williams, 1990; Dewey, 1913).

5.6 General Discussion: Revisiting Inquiry Through Design

In the preceding four sections, I have described the nature of student engagement in inquiry through design. Although aspects of student inquiry could be improved, students demonstrated the ability to generate their own questions about design ideas, plan investigations to investigate the merit of these ideas, and use the resulting empirical evidence to make decisions about the value of those ideas. Although students remained focused on improving their design throughout the project, the actions that they took, guided at times by both the teacher and the structure and prompts of the curriculum, led students on an experimental course that allowed them to explain their results in terms of specific design ideas.

Table 5.2 summarizes the main elements of student inquiry as I have described them here. In this section, I will discuss the role of inquiry through design in structuring and supporting student inquiry.

As I described in chapter 2, inquiry through design is comprised of four major elements: staging activities intended to prepare students for the design project, a design challenge that is both relevant and sufficiently complex to support student investigation, a structured design cycle modeled after a scientific investigation, and iterative redesign to allow students to apply their own findings to improve their design. Here, I will discuss how each of these elements fared in supporting student inquiry in the classroom.
TABLE 5.2.
SUMMARY OF STUDENT ENGAGEMENT IN INQUIRY THROUGH DESIGN

<table>
<thead>
<tr>
<th>Inquiry aspects</th>
<th>Student engagement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asking questions</td>
<td>• Students were able to generate their own questions to explore</td>
</tr>
<tr>
<td></td>
<td>• Student questions were tightly linked to the role of design materials and functional design properties</td>
</tr>
<tr>
<td></td>
<td>• Many meaningful student questions emerged from controversial ideas or surprising empirical results</td>
</tr>
<tr>
<td>Planning investigations</td>
<td>• Students succeeded in planning and conducting their own investigations</td>
</tr>
<tr>
<td></td>
<td>• Without guidance, students tended to plan exploratory rather than comparative investigations</td>
</tr>
<tr>
<td></td>
<td>• With limited opportunities to test, students combined comparative and exploratory approaches to form a hybrid investigation</td>
</tr>
<tr>
<td>Reasoning using data</td>
<td>• Students incorporated evidence and principles from staging activities, but only in instances when the activities shared materials with the design project</td>
</tr>
<tr>
<td></td>
<td>• Students were able to use evidence available to them to reason about design decisions</td>
</tr>
<tr>
<td></td>
<td>• Students rarely demanded evidence to justify design proposals</td>
</tr>
<tr>
<td>Pursuing explanatory goals</td>
<td>• Design goals dominated student investigations</td>
</tr>
<tr>
<td></td>
<td>• Design goals were reflected in extended exploratory investigation</td>
</tr>
<tr>
<td></td>
<td>• Explanatory goals arose in response to empirical discoveries</td>
</tr>
</tbody>
</table>

5.6.1 Staging Activities: Applying Scientific Principles to Design

Students’ use of staging activities to support their own design investigations differed in the Composites and Concrete classrooms. In the Composites classrooms, students rarely drew explicitly on the results of the staging activities. The primary instance of this was when students in Rachel’s class used results from the geometric reinforcement activity to inform
their use of fiber-reinforced tape. Students in the Concrete class were more successful
drawing on past experimental results, in part because these results were directly applicable
to their design: in both staging activities and the design projects students sought to identify
effective concrete formulations.

These results suggest that staging activities were most successful when they involved the
same design materials as the design project, making the applicability of the results obvious. However, other staging activities were designed to expose scientific principles that were applicable to student design, such as the importance of bonding composite materials together. Why weren’t these principles applied as often?

One possibility is that more time needs to be devoted to student reflection of the
connections between these results and the design project. While the existing staging
activities provide reflective questions that relate to design applications in general, these
questions are not explicitly related to the upcoming design challenge. In addition, the design
log sheets that accompany the design project might be changed to explicitly prompt
students to discuss the applicability of earlier findings in their design logs.

Another approach, which we saw in Doug’s class, is to make the results of staging activities
more easily accessible during the design task itself. Doug did this by posting results in the
back of the room. Posting these earlier results, or instructing students to refer back to these
results as part of the design planning process, might encourage students to use these results
to inform their design. This approach parallels student presentations of design results; both
support making evidence widely available for student consideration and critique. Similar
strategies have been used to support the sharing of design evidence in other settings
(Holbrook & Kolodner, 2000).

5.6.2 Design Challenges: Supporting Inquiry and Conceptual Understanding

In all three classrooms, we have seen that the design challenges students faced were
motivating and supported a range of design solutions among the groups in the class. In each
case, students quickly became involved in the project and were able to engage in the process
of inquiry as they worked to meet the design challenge. This was particularly important in
Doug’s classroom, where students set their own design challenges and tried to meet them.
Although this approach gives students a greater degree of independence and ownership
over their design project, it also raises the risk that students will select design problems that are too simple or too complex to be successfully investigated in the classroom. However, the students in Doug’s class proved capable of pursuing these investigations, suggesting that student-directed projects can be successful vehicles for student inquiry.

One concern with the design challenges was the difficulty students faced generating causal explanations for design performance. For the most part, explanations that were successful used empirical evidence to show the effect of a particular design idea. For example, Sarah, John, and Kathy’s first design isolated the effect of varying amounts of telephone wire on design performance (strength and stiffness). However, the group had trouble explaining the causal mechanism through which telephone wire would strengthen or weaken the overall design. Similarly, students in Doug’s class could not explain why certain ratios of cement, water, and aggregate led to stronger concrete; they could only point to evidence that demonstrated that a given formulation performed better than others.

These issues with causal explanation are in part related to the materials science focus of the Materials World Modules. The underlying processes that explain the strength or stiffness of a particular material occur at a molecular level, and design projects that only attend to physical materials will not uncover these processes. For example, students might be able to demonstrate that steel improves the strength of a design more than wood, but why, exactly, is steel stronger than wood? The nature of these design projects does not support student understanding at this level.

Hmelo faced a similar challenge in using the design of lungs to teach about circulation and respiration. Here, students constructed physical models of the lungs, but could not use the model to infer how the lungs transferred oxygen from the respiratory system to the circulatory system (Hmelo et al., 2000).

This issue may be less apparent in other design-based curricula that focus on scientific concepts like simple levers, mechanics, hydrodynamics, or propulsion systems (Kolodner et al., 1998; Penner et al., 1996; Sadler et al., 2000; Schauble et al., 1991b). These environments share with inquiry through design a focus on relating structure to function. They differ in that causal explanations may be successfully inferred from the structure itself. For example, classic high school design challenges like bridge building have traditionally focused on the geometric construction of the bridge rather than the specific materials used in construction.
In this case, geometry can be used to determine the distribution of force across the span and explain why some designs fare better than others. Domains where causality can be inferred from physical structure may prove more suitable than materials science-based design projects for developing scientific content knowledge.

5.6.3 Design Investigations: Structuring Inquiry

For students, planning, building, and testing their designs were key aspects of the design project. Inquiry through design’s approach of structuring the design process as an investigation was intended to help students plan better investigations and produce evidence that would inform their design questions.

We have seen that students were able to plan and conduct investigations that related design ideas to design performance. These investigations produced evidence that students used to reason about design ideas. Since inquiry through design is predicated on investigations of how structure effects function, it is reassuring to see that students were investigating these relationships.

We also saw that students did not always pursue comparative investigations during the design phase. A number of students chose to pursue exploratory investigations. These investigations allowed students to pursue more design ideas, but did not generate evidence that let students isolate the effect of specific design ideas.

Students who had the most success planning comparative investigations — the students in Lillian’s class — had the advantage of Lillian’s frequent guidance and support to help them shape their plans. Inquiry through design uses a series of written prompts to provide similar guidance. In fact, as author of the Composite module, Lillian helped to write these prompts. However, since the black line masters were not used in Rachel’s or Doug’s classroom, students did not have the opportunity to draw on this support, and there is no evidence to suggest whether these prompts would have been effective.

Given students’ tendency to focus on design goals and engage in exploratory investigations, it may be necessary to restructure the design investigation to provide better support for both exploratory and comparative investigation. While exploratory investigation did not generate comparative evidence, it was a source of student questions about design ideas. This suggests that a formal exploration phase, perhaps viewed as an initial design cycle,
may allow students to explore a range of design ideas. This exploration phase could be followed by one or more investigation phases where students attempt to isolate the effects of promising design ideas identified in the earlier rounds.

Providing students with a transition from exploration to investigation is appealing because it aligns well with Schauble’s interpretation of Dewey’s view that students will better understand the purpose of scientific investigation once they see how it will help them to understand a pragmatic problem (Dewey, 1913; Schauble et al., 1991b). However, the goals for each phase of the design project must be made explicit. We have seen that students persisted in pursuing performance goals even when they knew that they should be building explanations for their design ideas. Given the uncertainty surrounding the role of the written prompts, it may be necessary for teachers to help students understand the goals for each design phase.

5.6.4 Iterative Redesign: Opportunities for Further Investigation

Inquiry through design uses iterative redesign to create opportunities for students to pursue new investigations. In Lillian’s and Rachel’s classes, redesign allowed students to improve their designs. Within the observed groups, students were able to plan investigations to explore results from earlier design testing. For example, Sarah, John, and Kathy were able to explore the role of telephone wire in greater detail, while Lisa, Ellen, and Carrie were led by their design failures to search for materials that would meet a specific flexibility criteria. The questions that drove these investigations emerged from surprising or controversial findings from earlier investigations, suggesting that providing time for redesign allows students to discover and pursue interesting questions that help make inquiry more personal.

Redesign also allowed students in Rachel’s class to consider more design ideas that other groups generated. This created opportunities for students to evaluate others’ design ideas based on evidence, although — as we saw — Lisa, Ellen, and Carrie often took design advice at face value, even when it contradicted their own findings. These opportunities might be more productive if formal criteria were established to help students assess others’ design ideas. For example, Linn and Hsi have argued that establishing explicit criteria for critiquing work is an important means of helping students reason about evidence and argument (Linn & Hsi, 2000).
5.7 Summary

My goal for this chapter has been to describe the nature of student inquiry within an inquiry through design context. We have seen that students were able to generate productive questions, plan comparative investigations, and use the evidence from these investigations to reason about design decisions.

We have also seen that student engagement in inquiry varied across the three classrooms, due to the strategies the teacher used to enact the material as well as the nature of the design project and the students involved. Aspects of inquiry through design seemed to help support student inquiry in certain cases, such as the opportunities for redesign in Lillian’s and Rachel’s class and the use of staging activities to inform the design project in Doug’s class.

I have also raised concerns about some aspects of inquiry through design, such as the ability of students to generate causal explanations within certain design domains, and the importance of limiting exploratory investigation to the early stages of the design project.

These cases have provided insight into how students engage in inquiry in real classrooms and how inquiry through design contributes to that process. To understand how inquiry through design is supported in the classroom, I now turn to the role of the teacher. I have suggested in this chapter that particular actions of the teacher contributed to student inquiry, such as Lillian’s coaching students to plan comparative investigations and Doug’s placement of staging activity results where students could easily access them. In the next chapter, I will look more closely at the roles that teachers play in bringing inquiry through design to life and discuss the strategies that teachers use to help students engage in inquiry.
6.1 Moving Inquiry Through Design From Theory to Practice

In chapter 2, I introduced inquiry through design (ITD) as an approach that would foster scientific inquiry through carefully structured design projects. In chapters 4 and 5, we saw how students in three different classrooms were able, to varying degrees, to achieve success engaging in challenging aspects of inquiry. Students were able to ask productive questions that related functional design properties to design performance, plan comparative investigations to address these questions, and reason using empirical evidence to make design decisions.

We also realized that the nature of student engagement in each classroom was very different. For example, in one classroom, students received frequent coaching and generated a small number of comparative investigations. In another, students were given much more freedom to explore, and engaged in a series of exploratory investigations. Yet, teachers in each of these classrooms were working from the same written curriculum. What led to these differences in the practice of ITD? How do these differences affect student engagement in inquiry?

In this chapter, we will continue to examine the use of ITD in the classroom, turning our attention from the nature of student engagement to the role the teacher plays bringing ITD to life in the classroom. I will argue that the teacher’s role in interpreting and supporting ITD is critical to its success, and that we can in fact learn more about how best to support ITD by closely examining teacher practice. I will present analyses of a variety of strategies that three teachers employed to support ITD and relate these strategies to successful instances of student engagement in inquiry. I will discuss the success of these approaches from both the teachers’ perspective — taking into account their own goals, expectations, and experience — and the theoretical perspective of inquiry through design.
Finally, I will discuss the implications of this research on the ITD framework, and suggest ways to incorporate aspects of effective teaching practice in the written curriculum so that others may benefit from this work.

6.1.1 From Print to Practice: Teachers and the Written Curriculum

Why look at teachers? If the Materials World Modules reflect the inquiry through design approach, shouldn’t they suffice to engage students in effective inquiry in the classroom?

Although inquiry through design-based curricula are intended to support student inquiry, written materials alone do not dictate classroom practice. Scholars have documented the historical failure of curriculum-based reform, arguing that written curriculum – what curriculum developers and educational reformers produce for classroom use – bears little relationship to the taught curriculum – teachers’ interpretation of the written material (Cuban, 1993). This suggests that curriculum designers would do well to remember that teachers, not designers, enact curriculum.

There are several reasons why curriculum is transformed in classroom settings. Teachers teach in different ways. Research has shown that teacher’s understanding of the subject matter and teacher’s pedagogical content knowledge can both affect instruction (Smith & Neale, 1991; Tobin, Tippins, & Gallard, 1994). Teachers also have a strong tendency to adapt curriculum to fit with their own beliefs about teaching and learning, many of which were established during teachers’ own educational careers. These beliefs are deep-rooted and hard to change (Ball, 1996; Borko & Putnam, 1996; Kennedy, 1997).

Another important factor is the need to adapt curricular material to local contexts. Variations in available time, available materials, the age or reading level of the students, and the relevance of the proposed activities to students’ everyday lives all play a part in determining how curricular material is adapted to classroom practice. These issues are echoed in Ball and Cohen’s (1996) assertion that the nature of classroom practice is a collaborative negotiation among the teacher, the instructional materials, and the students. From this perspective, the written materials are but one of a number of contributors to the classroom learning environment.

These factors point to the importance of addressing the transition from written to taught curriculum in order to understand how innovative, reform-based materials translate to
classroom practice. Clearly, the teacher is a central figure in this challenging translation. Recent research efforts that have begun to study the enactment of curriculum in the classroom reflect an interest in understanding this process (Krajcik et al., 1998; Lampert & Ball, 1998; Marx et al., 1994).

6.1.2 Teaching Inquiry: Changing Roles

The role of the teacher in the translation of written curriculum to classroom practice is particularly relevant to inquiry-based approaches such as inquiry through design. Others have noted that as instruction moves from scripted, predetermined activities towards more open-ended, project-based work, the role of the teacher as a mentor and guide becomes crucial, even though that role has changed in ways that remove the teacher from the center of the classroom (Blumenfeld et al., 1991; Collins et al., 1989; Ritchhart, Stone Wiske, Buchovecky, & Hetland, 1998).

Adapting one’s practice to a new pedagogical framework — one that requires teachers to reflect on the manner in which they teach as well as the ways in which their students learn — can make the transition from written to taught curriculum particularly difficult. Studies of teachers using hands-on and inquiry-based curricula have shown that instruction varies from classroom to classroom (Minch & Bower, 1998). In some of these cases, the taught curriculum does not support student inquiry in the manner in which the written curriculum suggests (Germann et al., 1996; Olson, 1981; Welch, 1981).

Teachers who choose to use curricula like design projects in their classrooms do so with specific goals in mind. These goals may or may not align well with the goals of the curriculum designers and affect how the teacher presents the material and the expectations the teacher holds for what (and how) the students will learn. For example, a teacher may choose to use a design project because students do hands-on design work. The teacher may not be aware of or have no interest in, the inquiry aspects of the module. Under such conditions, it is not surprising that the enacted curriculum would differ from inquiry through design, for inquiry is not a supported goal.

Teachers may adapt written curricula in ways that reduce or obscure its pedagogical innovations. On the other hand, it is also true that teachers can breathe life into written curricula, enhancing innovation and fostering inquiry in novel ways. A written curriculum
is, at its heart, a didactic medium that does not 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, because it does not respond to students’ actions. That leaves substantial portions of instructional practice — including strategies for modeling inquiry, diagnosing student difficulties, and coaching students as they struggle with the challenges of engaging in inquiry— open to teachers’ interpretation.

As an example, consider inquiry through design. In this approach, as represented in the written Materials World Modules, students are encouraged to approach their design projects in a deliberative manner, planning investigations that vary only one variable at a time. Prompts in the worksheets that accompany the modules reinforce this approach for the students. However, as we have seen in chapter 5, students may stray from this approach and engage in more exploratory design. This might occur because students do not understand why varying only one thing is important, because they don’t bother to read the worksheet, because they think exploratory design is more interesting than controlled design, or any other number of reasons. What the teacher can do — that the written materials cannot — is talk to students, determine whether students understand the role of controlled experimentation, remind students of the explanatory goals of the project, reinforce these goals through explicit assessment measures, and so on.

6.2 Teaching Inquiry Through Design

Inquiry through design requires a teacher who can support student inquiry as it happens in the classroom. What insights and pedagogical approaches do teachers bring to support student inquiry? What kinds of support strategies help students to engage in inquiry through design?

The primary goal of this chapter is to identify specific teaching strategies that support student engagement in inquiry. I will focus on strategies that both reinforce and augment the ITD approach, and discuss whether some of these strategies may be abstracted into more general design principles for supporting ITD.

A secondary goal is to understand the decisions that teachers make in light of their own goals for their own students. These goals may be tangential to ITD or even conflict with it. However, a realistic view of classroom practice recognizes that part of the shift from written
curricula to taught curricula involves the teacher adapting instructional material to account for their own goals and classroom context. By characterizing each teacher’s decisions within a coherent context, we can explore the particular tradeoffs among strategies for supporting ITD and discuss how compatible these approaches are with other classroom factors.

Taken together, these two goals provide a broad view of how teachers support inquiry through design in realistic classroom settings. Documenting how teachers support inquiry through design in the classroom serves two purposes. First, it informs teachers and researchers of ways in which inquiry through design can be brought to life in the classroom. By providing strategies for teachers to use, this work can also inform the redesign of the written curriculum to reflect the effective approaches pioneered by experienced teachers.

Second, this work may provide us with a better understanding of the ways in which design, as an application and inspiration for scientific inquiry, can support science education. From this perspective, the work can inform other researchers and designers who seek to use aspects of design to build rich scientific learning environments.

6.2.1 How Do Teachers Support Student Inquiry Through Design?

In this chapter, I will describe how teachers support students engaged in inquiry through design. To do this, I will revisit the narrative cases with a renewed focus on the teacher and the ways in which the teacher contributes to inquiry through design in the classroom. I will focus on how teachers help students to address four challenging aspects of inquiry:

- generating and refining productive questions;
- planning and carrying out scientific investigations;
- reasoning about the results of these investigations;
- and maintaining an explanatory goal while engaged in an engineering task.

I focus on teachers’ strategic decisions, rather than more fine-grained instructional strategies, in order to provide a broad interpretation of teaching as a design practice in its own right. Strategic decisions reflect choices that teachers make about how they will adapt new curricula to their classrooms, how they will introduce it to their students, and how they will support student learning during the activity itself. Teachers can make strategic decisions to use specific instructional strategies — including particular discourse patterns, wait time,
and specific cooperative learning approaches — within the context of the design project. Where appropriate, I will describe these instructional strategies. However, unless otherwise noted, I will use the term strategies to refer to these higher-level strategic decisions.

Focusing on strategic decisions also allows me to consider the goals and rationale teachers bring to their decisions and to assess the implications of different approaches from the perspective of ITD. My goal is to provide a coherent account of the decisions teachers face and the decisions they make to support inquiry through design in practice.

My approach draws on prior work that seeks to describe the translation of another instructional approach — Teaching for Understanding — into practice. Ritchhart, Wiske, et al. focus on the strategic decisions teachers make that help to shape a climate supportive of Teaching for Understanding (Ritchhart et al., 1998). They ask: “How do teachers exemplify the abstract elements and criteria of the TfU framework in their own curriculum and pedagogy? What moves do teachers make when they teach for understanding” (Ritchhart et al., 1998, p. 122). This issue is not so much the specific instructional strategies teachers use as much as understanding how teachers enact core elements of an instructional framework.

I will distinguish among strategies that support student inquiry by reinforcing principles of ITD and strategies that support student inquiry by augmenting principles of ITD. Reinforcing strategies build on aspects of ITD that are already well defined and help us see how these principles play out in the classroom. Examples include implementing staging activities, treating design projects as scientific investigations, and providing time for iterative design. These strategies help bridge the gap between ITD as represented in written curriculum and ITD as enacted in classroom settings.

Augmenting strategies are approaches that are consistent with the aims of ITD, but extend it through novel approaches to supporting inquiry in a design context. We saw in chapter 2 that inquiry through design comprised a set of ideas and approaches for supporting inquiry within a design context. We also noted that ITD was a theoretical approach to instruction, one that we would need to examine in practice to understand how design contexts could support student inquiry. Augmenting strategies reflect ways of leveraging the design context to provide better support for student inquiry. These strategies may reflect existing aspects of teachers’ practice or new approaches that develop as a response to the design context. In either case, documenting these strategies is important because it can lead to the
refining of the inquiry through design approach and the sharing of these strategies with other researchers and educators.

The narrative cases in this chapter are structured roughly chronologically and are divided into two sections: how the teacher frames the design project, and how the teacher supports the ongoing design process. These aspects of teaching practice are informed by earlier work exploring the nature of the Teaching for Understanding approach in classroom settings (Ritchhart et al., 1998). In both cases, I will focus on strategies that reinforce and augment ITD.

Framing strategies are important because they define the nature of the task that students face. The framing of a project marks the initial translation from a written curriculum to a taught curriculum. Depending on how the task is presented, different affordances of design may be augmented or diminished. Teachers frame the design project for their students by deciding how much class time to spend on specific activities, making certain resources available for students, and setting expectations for student work. In addition to making lesson plans that reflect a particular framing, teachers also frame the task through their introduction of the activities, design project, and assessment measures.

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.

Touring strategies. Teachers also provide support for student inquiry throughout the course of the design task. In open-ended, student-centered classrooms, teachers often tour the classroom, moving from group to group in order to monitor group progress, reiterate expectations and provide guidance. These touring strategies, 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 by drawing on principles from the staging activities as well as evidence generated from earlier designs.

An important element of touring is the particular role the teacher chooses to adopt in the classroom. Teachers may adopt more active roles, playing the part of a guide or mentor working with students to solve hard problems. They may also choose to model the classroom after business or industry, and appoint students to specific roles while serving as manager or CEO. The choice they make about their role has implications for the frequency and nature of support that students receive.

Providing support for ongoing design allows teachers to reshape the taught curriculum based on the emergent experiences of the students. Teachers also have the opportunity to provide coaching to individual students and groups, and engage in more interactive discussions than would be possible in whole group settings. These discussions, and the strategies that teachers use to support student inquiry through these discussions, complement framing strategies by allowing teachers to respond to student inquiry. This reflects the two-way negotiation that occurs between teachers and students within Ball and Cohen’s model for classroom practice (Ball & Cohen, 1996).

Taken together, framing and touring strategies serve as complementary means of supporting student inquiry. The first serves as a formal means to introduce the task and communicate expectations for student work. The second serves as a means to track and respond to student engagement and provide individualized guidance for struggling students. Both sets of strategies can reinforce or augment the theoretical framework of inquiry through design. Framing strategies do this by interpreting the principles of ITD and reifying them in a lesson plan or assessment rubric. Touring strategies do this by addressing the challenges of engaging in inquiry and providing coaching and guidance for students facing these challenges. The narrative cases that follow describe and assess both framing and touring strategies in order to uncover aspects of teaching practice that reinforce and augment inquiry through design.
6.2.2 Integrating Inquiry Through Design Into Existing Classroom Practice

The main research goal for this chapter is to identify specific teaching strategies that impact student inquiry in design contexts. A secondary goal is to place these strategies for supporting student inquiry in a real world context.

Considering teaching strategies across classrooms helps us see how specific approaches contribute to student inquiry. However, certain approaches may not be as effective in another teacher’s classroom. My secondary set of research questions focuses on the contextual constraints that make these strategies work for specific teachers. Some approaches may conflict with some teachers’ existing practices or educational goals. Other approaches may have implicit prerequisites — including new assessment measures or classroom management practices — that make them successful.

Contextual constraints are particularly important because we know that teachers have difficulties adapting their practice in the face of various reform movements (Cohen, 1988; Cuban, 1993; Kennedy, 1997). These studies suggest that simply providing innovative curriculum is not sufficient to produce lasting changes in practice. This challenge is exacerbated for beginning teachers. More recently, educators advocating inquiry-based approaches in science education have questioned whether beginning teachers have sufficient preservice support to be successful using inquiry teaching techniques (Crawford, 1999).

Given these challenges, a secondary goal of this chapter will be to document teaching strategies within the context of their use: that is, to take into account the specific goals and constraints within which each teacher operates. The purpose of this analysis is to evaluate how the strategies each teacher uses form a coherent approach to supporting student learning in context.

I view this goal through the lens of design: instructional practice is a design task in itself. Such an view is consistent with recent calls to reformulate education research as a design science as well as recent characterizations of educators as reflective practitioners (Brown, 1992; diSessa, 1991; Gardner et al., 1990; Linn & Hsi, 2000; Schön, 1987).

The act of teaching shares many traits with the engineering design tasks ITD presents to the students. Teaching is a complex activity, 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 (Marx et al., 1994). As teachers modify their own practice over time, they must make sense of past instructional episodes 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 many opportunities 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. Strategies that effectively optimize performance — finishing the unit on time, getting students to understand the “right answer” — 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 may intentionally sacrifice one design goal in order to advance another. It is important to note that the “design criteria” implied here include the teacher’s own goals as well as those held by the designers of the instructional materials. The teachers’ framing of the task is informed by their own goals for instruction and student learning as well as their understanding of the instructional innovation at hand (Ritchhart et al., 1998). For this reason, we will review teachers’ instructional goals in this context to understand why teachers framed the task as they did.

Answering the core questions of this chapter — how teachers provide support to help students succeed with difficult aspects of inquiry — will rely on analyzing strategies across classrooms. Moving beyond these questions to issues of practice will require studying how these strategies are situated within specific classrooms. To do this, I will present an overview of instructional strategies for ITD within a teaching as design framework. Such a framework acknowledges that multiple teaching strategies may achieve similar results and that teachers may adopt differing strategies to address a range of design goals. The value of
such a framework lies in providing information that teachers new to inquiry through design curricula can use to support inquiry in their own context. Viewing teaching as an iterative design activity may also help developers of curricular materials to design curricula that take into account the needs and expectations of teachers with varying degrees of experience.

6.3 Data and Methods

This study is based on the three cases of classroom enactment of design curricula that we have already visited in chapter 4. In each case, the teacher used curricular units from the Materials World Modules projects, units developed around the principles of inquiry through design. Our goal for each of these cases is to understand how the teacher’s decisions affected student engagement in inquiry.

6.3.1 Classroom Setting: Revisiting Lillian, Rachel, and Doug

The design projects we have seen are situated in three different classrooms, each led by a teacher with whom I had extensive discussions about inquiry through design. Selecting teachers who brought a diversity of experience to ITD meant that I could examine a wide range of approaches to inquiry: some informed by prior experience with design; some informed by other professional experiences teaching science and inquiry. These teachers also brought a diversity of goals to their practice, providing an opportunity to compare strategies within the context of other classroom constraints, including competing learning goals and the teachers’ perceptions of student capacity for inquiry.

The three teachers represented in these cases — Lillian, Rachel, and Doug — represent a range of teaching goals and experience (see table 6.1). Each of the three teachers taught in a different high school in a different Midwestern city. Each brought significant expertise and experience to the teaching of inquiry through design. Lillian was co-author of the unit that she used (Composites). Rachel was not involved in curriculum development and was using the Composites unit for the second time; she had some prior experience with inquiry through design to inform her practice. Doug was using Concrete for the first time and had never used design materials in his class. These teachers’ backgrounds and expressed goals for the unit provide context for later discussions of each teacher’s approach to supporting inquiry, including how they viewed their role in the ITD classroom.
### Table 6.1.
**Teacher Experience Using Inquiry Through Design Curricula.**

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Module</th>
<th>Prior Experience with ITD Curricula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lillian</td>
<td>Composites</td>
<td>Lillian was a fourth year teacher and a co-developer of the Composites Module. She had previously taught the unit three times.</td>
</tr>
<tr>
<td>Rachel</td>
<td>Composites</td>
<td>Rachel 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.</td>
</tr>
<tr>
<td>Doug</td>
<td>Concrete</td>
<td>Doug had over twelve years of teaching experience, and had collaborated with educational researchers on other inquiry-based curricula. However, this was the first time he had used the Concrete Module.</td>
</tr>
</tbody>
</table>

In the remainder of this section, I will provide a brief overview of each teacher: their prior experience with inquiry through design, their goals for the project, and a review of project activities. With this as context, we will then move on to a closer examination of the framing and touring strategies that each teacher employed to support student inquiry.

**Lillian**

Lillian was a fourth year chemistry teacher at a suburban Midwest high school. She used the Composites Module in her regular level sophomore/junior chemistry class. A co-author of the module, Lillian 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. She used the module 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 before 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 Lillian assigned. 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.
Lillian’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 before the unit.

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, Lillian 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 of the project and providing support for student investigations was an important issue for Lillian.

In addition to the student-directed nature of the project, Lillian 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, Lillian 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.

Rachel

Rachel was a veteran science teacher at an urban high school just outside Chicago. She used the Composites module in her accelerated sophomore chemistry/physics class. (Rachel taught the chemistry half of the class.) Rachel had attended a weeklong summer workshop about the Materials World Modules and had taught the Composites module once before.
The observed class was one of Rachel’s four accelerated chemistry/physics classes. It met every day for a double period and 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; students turned in these notebooks at the end of the unit.

Rachel 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, Rachel 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, although Rachel’s experience with her first use of the module was 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 how she framed the design task, to address these issues.

Doug

Doug was an experienced chemistry and biology teacher at a suburban Midwest high school. He used the Concrete module in his regular level chemistry class. Doug had collaborated with university 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 spread across this time. (Because 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 was ready for testing.) The students spent a total of five days on the design project and did not do a redesign. Students worked in rotating pairs: Doug created new pairings for each activity throughout the module.

Doug 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 and allowing students to connect their scientific understanding to real world problems.

At the same time, Doug was concerned about the complexity that comes with providing such opportunities. 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.
Doug saw that students would need to make an “overwhelming” number of decisions over the course of the project. Because he had not taught the module before, he was not sure that students would be able to address those decisions within the duration of the project. Doug’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.

6.3.2 Classroom Data Sources

Data sources for my analyses of teaching practice parallel those used to analyze student engagement in inquiry. For each case, I conducted classroom observations throughout the module. In addition to field notes, I videotaped whole class discussions and small group work. Student work was collected or recorded. A pre-selected group of students participated in interviews following the module and I held ongoing conversations with the teachers to document their perspective and what they saw as the benefits and obstacles of the module. Teachers participated in semi-structured exit interviews following the completion of the modules. These interviews focused on the teachers’ goals for the module, their reaction to the unit, their view of the relationship between the staging activities and the design project, their assessment approach, their perceived role during the design project, and their ideas for how they might structure the unit differently, were they to teach it again.

In all classrooms I adopted a non-teaching role and offered suggestions about classroom practice only when directly asked by the teacher. This more neutral stance supported my goal of documenting how teachers adopted the materials to fit their own practice and the strategies they applied to support student inquiry through design.

6.3.3 Analysis of Framing and Touring Strategies

My analysis of teaching strategies that support inquiry builds on the narrative cases from chapter 4, using the chronology of the project as a framework for exploring specific claims about practice. I divided emergent teaching strategies into two general categories: strategies for framing the project, and strategies for supporting inquiry while touring the classroom. Each of these categories — framing and touring — imply a focus on specific classroom data sources.
Teachers’ framing of the project provides opportunities to reinforce aspects of inquiry through design and extend its principles through novel activities or assessment measures. To analyze teachers’ framing of the project, I documented each teacher’s lesson plan as implemented in the classroom and mapped the elements of the plan to specific elements of the written materials. This allowed me to compare the amount of time each teacher planned to spend — and did spend — on different aspects of the unit, including staging activities, initial design activities, and redesign. The match between the intended lesson plan and the written materials provided an initial benchmark of how the actual use of the module differed from the written version.

Teachers also framed the project activities by communicating assessment expectations to students. Teachers’ assessment approaches were tracked by documenting assessment instruments, reviewing how teachers discussed assessment with students, and devoting a portion of the follow-up teacher interviews to assessment practices. Inquiry through design encourages assessment that is consistent with an inquiry approach — focusing on explaining phenomena rather than producing better and better performance data — and I considered whether teachers’ assessment approaches reinforced this goal. Often, teachers’ particular approaches to assessment augmented inquiry through design by addressing teachers’ individual goals as well as inquiry goals; my analysis describes the nature of these measures and their relationship to these goals.

A final aspect of teachers’ framing of the project is their means of expressing to students the nature of design. Do teachers present design iterations as scientific investigations, or do they use other analogies or frameworks to help students understand how design and inquiry merge? I analyzed teachers’ introductions of the design project to their students, as well as later discussions with students and with researchers, in order to determine whether teachers employed specific analogies to introduce students to design.

Teachers also reinforced and augmented aspects of inquiry through design as they toured the classroom, helping students to engage in design. Touring strategies included techniques for deciding when to visit student groups, evaluating student progress and understanding, and providing coaching or mentoring support. I identified these strategies initially by reviewing videotape and field notes of student/teacher interactions. Strategies that were tentatively identified in this way were strengthened by looking for consistency over time as
teachers visited more and more groups. I also triangulated these strategies against other data sources including teachers’ self-reported goals in touring the classroom. Interviews with teachers following the unit also focused on teachers’ conceptions of their role in an ITD-based classroom and how that role differed from their normal teaching role. Teachers’ descriptions of their roles served to focus analysis further, providing an overarching context to which touring strategies could be related.

6.3.4 Generalizing Beyond Individual Classrooms: How Teachers Support Design

To interpret the emergent strategies for framing and touring and identify which of these strategies reinforce, augment, or contradict principles of inquiry through design, I looked across cases for instances of similar or varying strategies. The potential contribution of these strategies could be determined by relating strategies to the inquiry through design framework and by documenting teachers’ rationale for particular approaches. The contribution of these strategies in practice was determined by considering the impact of these strategies in terms of prior analyses of student engagement in inquiry (e.g. chapter 5). Those strategies that supported student inquiry and offered utility beyond a particular classroom context represent instances of how teachers support inquiry in design settings.

6.3.5 Seeking Coherence in the Integration of Inquiry Through Design Into Classroom Practice

In addition to identifying individual strategies for success, I also looked at the tradeoffs teachers faced over the course of the unit. These teachers incorporated their own goals, understanding, and experience into the teaching of design projects. Rather than simply analyzing their practice based on my own goals for inquiry through design, I adopted an approach, similar to that used by Ritchhart and Wiske (1998) that draws on their own goals and ideas to better explain why they chose particular instructional strategies. I draw heavily on interviews conducted with the teachers before and after the modules were used. These interviews focused on the specific goals each teacher had for the unit, the rationale for specific decisions that were made during the unit, and the teacher’s reflections on the overall success of the unit and what they might do differently the next time. Ongoing study of the narrative cases, particularly later interactions with students in which the teacher reified elements of this framing, provided additional evidence for these characterizations.
6.3.6 Summary

The remainder of this chapter revisits the narrative cases from each of the three classrooms, structured from the teacher’s perspective. In each case, I will address my primary research questions by exploring how each teacher reinforced and augmented student inquiry through design. In order to present a coherent view of each teacher’s practice, I will also consider how each teacher’s own goals and expectations for the unit shaped the strategies that were used. I 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.

Following the three cases, I will discuss general strategies that cut across classrooms. These strategies will form the basis for a core set of teaching principles that appear to support student engagement in inquiry through design. I will organize these strategies around the four challenges to student inquiry: generating productive questions, planning effective investigations, reasoning with data, and maintaining an explanatory goal. Finally, I will discuss some of the tradeoffs that appear inherent in these strategies, and suggest means for teachers to determine how these strategies will contribute to student inquiry in their own classrooms. 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. I will use these cases to begin to build a model that explains how different support strategies contribute to inquiry within design contexts.

6.4 Lillian: Teacher as Guide

Lillian was a co-author of the Composite module. Familiar with inquiry through design, she viewed her role as that of a guide, helping her students to design scientifically sound investigations to explore design ideas.

In this section, I will review the decisions, strategies, and approaches Lillian used to frame the project and support student inquiry over the course of the project. I will focus on the implications of her decisions from the perspective of inquiry through design, and consider these actions in light of Lillian’s own goals for the project and her students. I will first focus on how Lillian framed the project, touching on her lesson plan, her assessment plan, and how she chose to introduce the project to her students. Then I will discuss her approach to
touring the classroom and working with students in smaller groups to support their learning.

Finally, I will relate these actions to what we know from chapter 5 of student engagement in inquiry in Lillian’s classroom and discuss how specific teaching strategies supported student inquiry.

6.4.1 Framing the Project: Buying Time for Redesign

Lillian taught the Composites module during the two weeks leading up to the winter holidays. She, along with the other chemistry teachers at her school, had decided that they could spend six days on the project. However, the students had to be done by the sixth day, because it was the last day of school before the break.

The Composites module, as written, consists of four main staging activities followed by the design project (see Appendix A for descriptions of each activity). Taken together, the staging activities, design project, and redesign normally take between one and two weeks of class time. Lillian had to fit the module into six days.

<table>
<thead>
<tr>
<th>TABLE 6.2. LILLIAN’S SCHEDULE FOR THE COMPOSITES MODULE.</th>
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<td>Day</td>
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In order to devote the majority of time to the design project — including a redesign phase — she planned to cover three of the staging activities in the first day and dropped the fourth activity entirely. By moving quickly through these activities, Lillian could introduce the design project on the first day and give her students three full days to work on planning, building, and testing their first set of designs. This schedule (see Table 6.2) would also allow students two days at the end of the project for redesign.

With less than the optimal amount of time for the module, Lillian had to cut some corners. Her decisions reflected her reasons for wanting to use the module: to give students opportunities to engage in more open-ended investigations. Following the module, Lillian spoke of the tendency for students in science classes to focus on the correct answer.

...what they should have seen, what they should have learned, what they should have calculated, and then they have to learn what they should have seen, and use it. So, I really think that this is a valuable time for them to see that science isn't always what you should have seen.

Rather than focusing on a “right answer” — the answer you should have seen — Lillian focused on the design project as a way to encourage students to try to make sense of the empirical results they found.

We don’t encourage them to think very often. We encourage them to write and to do, and then to listen, and then remember, but not actually think through it themselves. Even with a lab, we’ll have them do a lab, and they’ll come back and we’ll tell them what they learned. We don’t have them ever really think and tell us what they learned. At least not very often.

When faced with the need to cut something from the module, Lillian chose to cut the staging activities rather than the design project because the staging activities did not directly address this goal: they were intended to uncover specific scientific principles. The design project, and the redesign phase, did address this goal.

Although Lillian bought her students two days to redesign their design projects, these days came at the expense of the staging activities, which were shoehorned into just over thirty
minutes of instructional time. (By comparison, Rachel, who used all four staging activities plus a fifth optional activity, averaged slightly over thirty minutes on each activity.)

From the perspective of inquiry through design, Lillian’s scheduling decisions have two potential implications. First, by abbreviating the staging activities, it is possible that students would have less time to reflect on how the scientific principles in each activity could contribute to the design project. For example, the foam composite activity helps students to see how defects—places where constituent materials are not well bonded—affect the physical properties of the composite. Understanding this principle has direct implications for design, because it suggests the importance of adequately bonding (e.g. gluing) materials together to improve design performance. With less time to reflect on these results, students might not think to apply the principle later, when they were planning and building their own designs.

The second implication is more optimistic. By providing two days for redesign, Lillian created enough time for students to engage in a second investigation. This would allow students to pursue questions that arise from the initial design phase, perhaps investigating surprising or anomalous test results.

6.4.2 Framing the Project: Assessing Investigation

During the second day of the module, Lillian handed out her grading rubric (see Table 6.3). She went over it with her students, explaining what she expected in each of the rubric categories. The rubric reflects a mix of already existing classroom norms and categories that related directly to the design project. For example, the first category addressed collaborative work using the SCORE acronym: an assessment practice that was used throughout the school year.

The majority of rubric was devoted to students’ work on the design project. Two omissions stand out. First, student work on the staging activities does not factor into their overall grade. This is consistent with Lillian’s scheduling emphasis on the design project rather than the staging activities.
The other interesting omission 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, the two main performance measures students used to evaluate their design. Instead, Lillian explained that their grade was based primarily on how they engaged in the design process, including their ability to use the design task to investigate a question, to make predictions about that question, and to reconsider their predictions in light of their results. The rubric also emphasized the redesign. Planning scientific investigations was an important part of the redesign as well; students were expected to build on their first design by identifying a new variable to explore and planning a second investigation.
Lillian’s assessment practices, as represented by her rubric and her explanation of the rubric to her students, addressed an important inquiry through design principle: she intended to use assessment to focus student work on explanatory goals. This is evident in the lack of value placed on design performance, and the structure of the rubric to mirror the investigation process. Lillian gave her students reasons to care about the process of investigation.

On the other hand, the omission of staging activities from the rubric — combined with the lack of time spent on the activities — suggested that these activities were not the focus on the module. While it is true that the staging activities were not the focus, they were designed to contribute to students’ conceptual understanding of composite materials and inform the design process. We shall see whether assessing these activities is necessary to encourage students to apply their principles to design decisions.

6.4.3 Framing the Project: Introducing the Design Challenge

Lillian introduced the fishing pole design project towards the end of Day 1. To introduce the challenge she had students read the introductory text in the written curriculum. This text outlines the primary design challenge, couches the challenge within a motivational setting, and gives students a sense of the scope of the task.

Catch More, a fishing supply company, is holding a contest for the design of a new fishing pole. The winning fishing pole will be made of a composite material. Enter the contest and take up the design challenge!

Your group will be given a set of drinking straws to use as a base for your prototype design. With your group, you will design, construct, and test a set of prototype fishing poles; after you evaluate your design and have it critiqued by others, you will have an opportunity to redesign your fishing pole based on what you learned from working on your design.

While this introduction provides the general framing of the design challenge, it leaves several questions open for student investigation, such as the important attributes of a successful fishing pole. After students had read the introduction, Lillian led a class discussion to decide what properties their fishing poles should have. In this discussion,
Lillian let students suggest properties while providing guidance to focus students on properties that would apply to the pole itself, rather than other aspects such as the reel, the fishing line, or the lure.

**TEACHER** Ok. We're going to set this up... what we need to do is write a proposal for making this fishing pole. We're going to try to figure out a way to make a fishing pole where... what would we want a fishing pole to do?

**STUDENT 2** Bend, but not break.

**TEACHER** We want it to be flexible, but we don't want it to break, so we want it to be...

**STUDENT 3** Strong.

**TEACHER** Strong. Strong, flexible, anything else we want our fishing pole to do?

**KATHY** Have a big string.

**TEACHER** What?

**KATHY** Have a big string, to reel in the fish.

**TEACHER** Ok. We're actually not going to worry too much about the string. We're going to worry just about the pole.

Lillian helped the students to translate realistic expectations for the fishing pole (“bend, but not break”) into specific properties for the project. In this case, strength and flexibility are two properties that the students have just finished exploring in the staging activities. They are also two of the three properties which are suggested by the written curriculum; Lillian used the class discussion to get students to articulate these properties before reading about them in the text. Later in the discussion, students add two more properties: mass and being waterproof. Although ‘waterproof’ was not a property that she had anticipated, Lillian let the students decide whether they would include it in their design. Reasoning that “we’re not going to be using” the fishing poles, the students decided not to test their designs to see if they are waterproof.
Lillian went on to explain how students would engage in design investigations. As part of their designs, she instructed her students to identify one variable that they would explore by building a set of designs. The purpose of having a variable was to vary only one thing at a time, so that the data students generated would speak to the effect of that one variable. As Lillian put it, “if you start varying a whole lot of variables at a time, it gets confusing.”

Students were still allowed to apply multiple design ideas — 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 include all of these ideas except for the one variable.

Investigation in the redesign phase was similar to the initial designs, with students again investigating a specific variable. On Day 4, after students had tested their first set of designs, Lillian encouraged students to take the best design from their first set of variants, and then modify it to explore the effect of another design idea.

Lillian’s framing of the design challenge as a scientific investigation directly reinforced a central principle of inquiry through design: to structure design around investigations. By encouraging students to investigate one design idea at a time, Lillian provided a scaffold for investigation that should contribute to students’ success planning comparative investigations, a core aspect of inquiry. By also structuring the redesign around investigation, Lillian gave her students two opportunities to plan good investigations and the opportunity to use the empirical data from the first set of designs to inform the redesign.

It is not surprising that Lillian’s framing of the project aligns well with inquiry through design. She co-authored the curriculum. In interviews prior to the unit, she had stated that planning good investigations was one of the hardest, but most important, inquiry skills that her students needed to be able to do. Her scaffolding of design investigations was a response to that goal.

The implications of this approach on student inquiry are consistent with inquiry through design. By reinforcing the idea of treating design cycles as investigations, we would expect to see students engaging in the planning of comparative investigations and, as a result, generating empirical data that they can use to reason about design performance.

Lillian also used presentations to create a climate where students shared design ideas. She framed two presentations, one before building the first set of designs and one after 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. Lillian 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.

The use of these presentations augmented the inquiry through design curriculum by providing a mechanism for sharing information across groups. Inquiry through design advocates sharing the results of design investigations but does not provide specific mechanisms to support this sharing. Student presentations are one way to achieve this. In addition to addressing communication, Lillian also hoped the presentations would serve to reduce competition and its attendant focus on design performance: a goal shared with inquiry through design.

6.4.4 Touring: Teacher as Guide

Framing the design task for students is one way to structure student engagement in inquiry. Teachers also support student inquiry while students are working on the design task.

To support student inquiry during design, Lillian adopted the role of a guide or mentor: visiting groups, asking questions to gauge student progress, and offering advice or feedback on each group’s design. Her work here aligns with instruction in a cognitive apprenticeship model, in that she both models and scaffolds student inquiry, fading her guidance over time (Collins et al., 1989).

Lillian toured her classroom almost constantly. Unlike some teachers, who often return to a “home base” — such as their desk or to the front of the room — between trips around the classroom, Lillian 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 Lillian’s touring to ask her questions, although given the frequency of her visits, this isn’t surprising; there was no shortage of opportunity to speak with her.

When she toured, Lillian 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.

Lillian 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 composite materials together.

Lillian 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.)

Lillian also tried to help students apply their scientific understanding to their design, particularly focusing on the importance of bonding materials together. She repeatedly reminded the focus group that they needed to bond their materials to the straw in some way. She referred to the staging activity they had done which showed that a foam composite with incomplete bonds 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?

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. Lillian was visiting each group, soliciting their predictions for the performance of their designs. In this example, Lillian is focusing on helping students to define their variable.

**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 Lillian’s touring style. First, she elicits the group’s predictions—her main goal for this touring cycle. The group’s predictions are very general, and as she probes Lillian 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. Lillian 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.

Lillian also modeled aspects of inquiry for students by drawing on work that students did in previous years. These examples served to illustrate the kind of comparative designs she expected from her students. 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 one design idea, a fact that some students had not realized.

Lillian faded her scaffolding over the course of the project as students became more familiar with design investigations. This is visible in Lillian’s touring during the redesign stage. At this point, groups have completed one design cycle and are planning their second design investigation. They understand what they are expected to do. Rather than immediately initiating conversations with each group as she tours, Lillian is instead more willing to sit back and just listen to a group’s discussion to judge their progress.

An example from the redesign phase illustrates this point. Here, the students are arguing over the nature of the variable they will investigate in their redesign. The student discussion is at a higher level than during the initial design, where students did not recognize the need for a variable and could not articulate what theirs was when Lillian visited the group. Lillian joins the group and listens to their argument.

SARAH Yeah, except that our variable is now... we have to keep our variable the same, so... (KATHY: Yeah.) if we do all little wires...

(TEACHER joins group, sits down next to JOHN.)
JOHN  But isn't it all wires? Isn't it still wiring?

SARAH  It's the number of little wires.

KATHY  The number of thin wires.

SARAH  So it's... if we have four thin wires the next time, and six the next time, and eight the next time, blah blah blah blah blah. Then we have to keep going like that. Otherwise, we...

JOHN  Well, can't we say that it's thick and thin wires? That vary? I mean this is only...

SARAH  But we have to keep it constant. It's not like we can just generally... let's do some this way and some that way.

JOHN  You can't change this and the little wires at the same time? You can't say this is zero/eight thin, zero heavy/eight thin and then do one heavy and four thin?

SARAH  Oh yeah. We can do that.

TEACHER  So that would be the ratio of thick to thin wires. That's your variable?

Rather than intrude with her own question, Lillian instead lets the argument play out, and then rephrases John’s definition of a variable to help him articulate his idea. With that, she moves on.

Lillian’s touring style was strongly geared towards supporting one important aspect of inquiry: students’ ability to move from an initial design idea to plan an investigation that would assess the effect of that design idea. By engaging in frequent interactions with groups and pushing students to articulate key elements of their investigations — their variable, how they were constructing their designs, and their predicted results — she kept students focused on design as investigation rather than exploration. The emphasis on incorporating a single variable into each set of designs, combined with the guidance Lillian 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 of the
most flexible fishing pole in their first set of designs was wrong. This finding led the group to focus their redesign on investigating what made their most flexible design work.

This approach reinforces a core element of inquiry through design. Consequently, we would expect to see students have more success planning investigations and reasoning about the data these investigations produce. In the following discussion, we will revisit student inquiry in Lillian’s classroom, and consider how her practice contributed to successful engagement in difficult inquiry tasks.

6.4.5 Discussion

We have seen a variety of strategies that Lillian used to frame the Composites module and support students engaged in inquiry and design tasks. How well did these approaches support inquiry through design?

To address this question, we will review the analyses of student inquiry from chapter 5, where I explored how successfully students were able to engage in different aspects of inquiry in Lillian’s classroom. Summarizing briefly, we saw that:

- Students generated productive questions better during the redesign phase — where the questions emerged from initial empirical results — than they did during the initial design phase. At first, students didn’t seem to understand the importance of the question and felt that defining a variable was a chore, not a compelling course of inquiry.

- Students were able to plan and conduct comparative investigations of their design ideas. Of the three classrooms, students in Lillian’s class seemed to produce the best investigations.

- Students used empirical evidence to reason about their design results, and this evidence informed later questions that the group explored. However, students were less successful at drawing on results and principles from the staging activities to inform their design.

- Finally, students maintained an explanatory focus throughout the project. Compared to the other classrooms, students in Lillian’s class did not explore as many design ideas, but they investigated the ones they did explore in more detail.
How do Lillian’s strategies for framing the task and supporting inquiry relate to these results? When I discussed her approaches, I outlined specific implications of these actions from the perspective of inquiry through design. Now, we will look to see how these implications align with empirical evidence of student inquiry.

Lillian made a choice when scheduling the project to provide time for redesign at the expense of staging activities. The redesign phase of the project proved to be important for several reasons. First, it provided opportunity for students to explore emergent questions. Unlike the initial design phase, the question the focus group explored in the redesign came directly from their test results. Second, it provided students with another opportunity to plan an investigation — an aspect of inquiry that students in Lillian’s class engaged in quite successfully. Lillian’s decision to focus on design, and particularly redesign, reinforced the ITD principle that iterative redesign is a critical part of using design contexts to engage in inquiry.

The tradeoff in her scheduling time for redesign, of course, was a lack of time to reflect on the results of the staging activities. Despite Lillian’s efforts to scaffold the application of these results during design — such as the importance of bonding materials together — students seemed to incorporate bonding into their designs at Lillian’s behest, rather than through a conceptual understanding of the role of bonding in composite materials.

Given the limited amount of time to run the module, something clearly had to go. The ineffectiveness of the staging activities at informing later design decisions suggests that, were more time available, students would benefit from reflection on these activities. However, we will explore this point more closely in Rachel’s classroom, where substantially more time was allocated to staging activities.

Through both her assessment rubric and the use of presentations, Lillian deftly sidestepped the issue of competition, which often emerges in design settings and biases students to adopt more empirical performance goals. Although reduced competition was a stated goal, Lillian was nonetheless surprised at how well it went.

One thing, I don't know if I stated it as a goal or not, but I'm trying to work on it more this year, is to try to foster cooperation instead of competition. To not have teams versus other teams. And I think it worked really well in my class. I was really
impressed with how much they didn't say 'Mine's better than yours. Ours is better than yours. Yours broke.' They just... they didn't do it at all. I don't know if it was something I did, or whatever, but I was really impressed with how it didn't turn into a competition.

Lillian later credited her focus on presentation as one means for accomplishing this; students’ design ideas were made public rather than kept secret. However, other factors came into play, because groups, even before the first presentation, did not display any evidence of competition. Lillian’s framing of the task contributed to this. With no aspect of assessment dependent on performance, students were free to explore and improve on ideas that they found interesting. Her introduction of the design project led to a discussion of important design properties, but downplayed the focus on developing a “winning fishing pole” that was described in the written materials. The lack of competition, combined with a strong focus on design investigations during the project, may have helped students to balance the engineering aspects of their design with inquiry into the factors affecting their design.

Lillian’s role during the design project, touring the room and providing guidance for student investigations, was an important element in students’ success planning comparative investigations. Early interactions helped students to identify appropriate variables and understand the need for these variables. By pushing students to articulate their variables and design variants early, she kept students focused on investigation rather than more exploratory design. Structuring these investigations proved crucial, because it meant that students were able to generate comparative data, which in turn led to the emergent questions that drove the redesign. Through her touring strategies, Lillian augmented the intent of inquiry through design by providing mentoring and coaching support attuned to the needs of the group. This was visible in her willingness to listen to students argue about their investigations in the redesign phase of the project. Her case provides a model for how to support inquiry through design in classroom practice.

In the general discussion, we will return to this case to identify teaching strategies that seem promising enough to support inquiry in a variety of classroom settings. First, we will move on to discuss another teacher who may provide another model for supporting inquiry through design.
6.5 Rachel: Teacher as Project Manager

Rachel was using 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 to reduce competition and improve student investigation. She saw herself as a project manager: a role that allowed students autonomy to design and served as a resource if they needed help.

As in the previous case, I will review the teaching strategies Rachel used to frame the project and support student inquiry, focusing on the implications of her decisions on student inquiry.

6.5.1 Framing the Project: Time for Staging Activities

Rachel taught the Composites module early in the school year, about a month after the start of classes. The class was a combined physics/chemistry class. Rachel normally alternated instructional days with the physics teacher, so students would have chemistry class every other day for ninety minutes. However, this project took place during a time when the physics teacher was ill, so students completed the project over five consecutive days.

Rachel had taught the module the year before, also in the early fall. Then, she taught the module in four days of double periods, and did not incorporate a complete redesign. This time, she added a day to allow more time for redesign.

Although Rachel had only five days for the module, she was working with ninety minute double periods, and so had substantially more instructional time than Lillian. Rachel used all of the staging activities, including an optional activity where students explored the effect of directional reinforcement by wrapping fiber-reinforced tape around a foam beam in different ways. (For descriptions of the staging activities, see Appendix A.) Rachel spent about half of this time on the staging activities and half on the design project (see Table 6.4).

By spending two and a half days on five staging activities, Rachel provided significant time for students to complete the activities and reflect on their results. Students used their lab books to document results for both staging activities and the design project, implying that the results from these activities were accessible to the students later in the 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. Rachel also introduced a research project that 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 common 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 geometric reinforcement activity, after which Rachel introduced the design project.

Students began exploring their own design ideas towards the end of day three. Although they did not yet have a chance to bring in their own materials, they were able to explore some of the materials from earlier activities — plastic rods, wood skewers, and string — that were compatible with the fishing pole design. Day 4 was the main design day. Students brought in materials, built, and tested their designs. On the final day, students had half the period to redesign and test their fishing poles (the other half was devoted to physics and the return of the physics teacher). Students were to turn in their lab books, containing their results, conclusions, and their reflections on the unit, within four days.
Rachel’s schedule reflected a lesson plan that stayed fairly close to that suggested by the written materials. Her schedule was quite similar to the previous year, as she chose to spend significant amounts of time on staging activities, and just over one day on the main design task. With an extra day, she added time for a more structured redesign phase. With balanced time for staging activities, a main design phase, and a redesign phase, her lesson plan reflected all the major components of inquiry through design.

Rachel did change the nature of the project somewhat from the previous year. This time, she expected students in a group to work together on a shared set of design ideas, and to plan a design investigation around one or more of those ideas. The year before, she had let each student in a group build their own design, which led to intra-group competition and a lack of comparative investigation. Rachel described the previous year’s approach in a follow-up interview.

I had each person in the design team, that’s right, 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 ... it wasn’t a controlled experiment.

This change structured the project to better match the inquiry through design approach, where design cycles become scientific investigations. Rachel describes the change, and what she saw as the potential benefits of the change, in the follow-up interview.

So, the prototypes much more got along the line of a controlled experiment where they were just changing one thing for the most part ... many of them did just vary one thing and that allowed them to learn more. So, the redesign made sense. Because that ... and, and, having them learn from each other in the class made sense.

Because, ideally, now they’ve got new information that they use to do something.

Such an approach implied that students will have greater opportunity to engage in the planning of scientific investigations and reasoning about the results of those investigations than if each student in a group worked on their own, individual design idea.
6.5.2 Framing the Project: Using Assessment to Balance Competition and Motivation

Rachel had two main goals for assessment. First, she wanted to reduce the amount of competition in the classroom. Rachel had firsthand experience seeing how the competitive, design performance goals of the project could come to overwhelm inquiry goals. When she had run the project the previous year, students had waged ‘industrial espionage’ on each other and went to great lengths to prevent anyone, including Rachel, from learning about their design ideas. Although Rachel was thrilled with student motivation and engagement, she wanted to create a more open, collaborative environment where students could work together to learn about their designs. Rachel described her experience this way.

...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.

Second, Rachel decided to focus students’ writing on their lab books, rather than requiring a formal lab report. This change was meant to focus students’ attention on explanation and evidence rather than the format of a formal report, where students were, in Rachel’s words, “just filling the pages with words rather than really analyzing because they were worried about the paper, and the format, and everything else.” The new focus on students’ lab books was, as Rachel says here, driven by an interest in getting students to use evidence to support conclusions about the contributions of different design materials.

So ... I decided to get away from that to, um ... to kind of take the pressure off and just ... really push this one section in the lab book on the conclusions for the design lab and that was ten points out of twenty-five where they really needed to ideally go
through what were the materials, what was the evidence [that the materials worked] and why ...

Rachel’s grading rubric placed an emphasis on documenting the design investigation and drawing conclusions about design performance that were supported by evidence (see Table 6.5). Much like Lillian’s rubric, it does not value overall design performance at all, focusing instead on the investigation: documenting the procedure, recording data, and drawing conclusions based on that data. In addition, student work on staging activities is assessed, an approach consistent with the amount of time spent on these activities. Finally, a fifth of the rubric is devoted to a “learning log” — students’ reflections of what they learned from the unit and why.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>1</td>
</tr>
<tr>
<td>Recorded unit notes, directions in lab book</td>
<td></td>
</tr>
<tr>
<td>Ice Composites</td>
<td>1</td>
</tr>
<tr>
<td>Predictions, data, and conclusions in lab book</td>
<td></td>
</tr>
<tr>
<td>Composite Hunt</td>
<td>2</td>
</tr>
<tr>
<td>Students received 0 points for finding 0-3 materials, 1 point for 4-7, and 2 points for finding more than 8.</td>
<td></td>
</tr>
<tr>
<td>Strength and Stiffness</td>
<td>1</td>
</tr>
<tr>
<td>Predictions and data in lab book</td>
<td></td>
</tr>
<tr>
<td>Graphed results in grid</td>
<td>1</td>
</tr>
<tr>
<td>Definitions and conclusions</td>
<td>1</td>
</tr>
<tr>
<td>Foam Composites</td>
<td>1</td>
</tr>
<tr>
<td>Data chart</td>
<td></td>
</tr>
<tr>
<td>Graph of data</td>
<td>1</td>
</tr>
<tr>
<td>Geometric Reinforcement</td>
<td>1</td>
</tr>
<tr>
<td>Predictions, data, and conclusions in lab book</td>
<td></td>
</tr>
<tr>
<td>Design Project</td>
<td>3</td>
</tr>
<tr>
<td>Initial Design:</td>
<td></td>
</tr>
<tr>
<td>Procedure</td>
<td>1</td>
</tr>
<tr>
<td>Data</td>
<td>1</td>
</tr>
<tr>
<td>Conclusions</td>
<td></td>
</tr>
<tr>
<td>Redesign:</td>
<td>3</td>
</tr>
<tr>
<td>Procedure</td>
<td>1</td>
</tr>
<tr>
<td>Data</td>
<td>1</td>
</tr>
<tr>
<td>Conclusions</td>
<td></td>
</tr>
<tr>
<td>Learning Log</td>
<td>5</td>
</tr>
<tr>
<td>Described five things they learned from doing the project. Students received one point for each thing they learned.</td>
<td></td>
</tr>
</tbody>
</table>
Perhaps unsurprisingly, the prior year’s difficulties surrounding competition in the classroom arose in part from Rachel’s grading practice. What is interesting is that this resulted not from her rubric, which was similar to the rubric shown above, but from a small amount of extra credit points that Rachel used as a carrot to motivate student interest in the project.

The extra credit scheme that had led to such competition the previous year arose from Rachel’s framing of the design project. Rachel had presented the design project as a competitive engineering challenge, where each group was competing against other groups to design the best fishing pole. Rachel had reinforced this by offering five extra credit points to the one group that produced the best design of all four of her classes. Despite the fact that nothing in the twenty-five point assessment rubric valued design performance, the presence of a five point ‘trophy’ resulted in a highly competitive atmosphere in which groups hid their work from each other, and even from Rachel, for fear of “industrial espionage.”

Rachel’s solution this year was to keep the extra credit bonus, as it did increase the interest level of many, but not all, students in the class. 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.

Much as Lillian did, Rachel constructed an assessment measure that rewarded the investigation process, including making conclusions that used evidence to support claims about design performance. Her rubric, which also rewards students for participating in staging activities, is consistent with her decision to spend substantial time on staging activities.

Rachel differed from Lillian in choosing to use extra credit to reward students for design performance. She carefully constructed the extra credit opportunity, based on prior experience, to foster collaboration within the classroom, while fostering competition across classrooms. This strategy is particularly well suited to inquiry through design, because it acknowledges the dual goals that design and inquiry bring to the table, and manages to find a way to appeal to both. Evaluating the success of this approach will depend on whether it succeeds in motivating students without allowing performance goals to dominate in the classroom.
6.5.3 Framing the Project: Introducing the Design Challenge

Rachel presented the design project as a challenge, one in which the class would work together as several collaborative groups. Rather than having students read the written introduction, Rachel introduced the activity herself. In her introduction, Rachel explained how each group would build three prototypes (or design variants), test these prototypes, and then build one final design based on the results of the initial testing. She then asked the class to identify the properties that they thought were important for a fishing pole. Students suggested the properties of strength, flexibility, and, with some hints on Rachel’s part, weight. These three properties corresponded to those in the written materials. Students did not suggest any other properties.

Rachel encouraged students to think about what they had learned from earlier activities and to choose materials that had the properties that they had identified as a class. Rachel also encouraged groups to plan comparative investigations similar to those in Lillian’s class, something that did not happen the year before. After suggesting a local art supply store as a potential source for design materials, Rachel explained that each group’s three prototypes should vary only one feature so that they might compare specific design elements. As an example, she described a hypothetical design that used tape and uncooked spaghetti; one might wrap a fixed amount of tape around each prototype, but vary the number of pieces of spaghetti used to reinforce the inside. The point, she said, was to vary a single element so that one could point to that variable as the reason for changes in the design’s performance.

Rachel also described the method by which students would test and compare their designs. Based on the prior year’s experience, where students had difficulty determining exactly when a design had failed (or cramped), Rachel explicitly reviewed three definitions for design failure.

Rachel showed the class two designs from the previous year to make it clear that multiple design approaches could succeed. One design was heavy, but quite strong; the other, lighter and weaker. However, design performance was measured using a strength-to-mass ratio, which meant both designs were successful. By showing these examples and describing their test results, Rachel helped set student expectations for good design performance.
Rachel described the redesign as a chance for students to vary another design element from their first set of designs or to try something completely different. What was important, she said, was that students ultimately justify their design decisions based on what they had learned from their own design as well as others’.

To encourage sharing design ideas, Rachel planned to use student presentations to encourage the spread of design ideas within the class. Prior to the redesign, she said, students would share what they had learned with each other, giving students additional design ideas to consider. 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 that students needed the extra time to finish building and testing their designs and that many students lacked experience giving successful class presentations. Rachel 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, Rachel 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.

Rachel’s introduction of the design challenge drew heavily on the written materials, but augmented these materials by encouraging the class to work together as a whole in order to compete against other classes. Although Rachel presented the project herself, rather than having students read the written materials, her introduction aligned well with inquiry through design principles by presenting the design process as an opportunity for investigation. She modeled a good comparative investigation and used examples from the previous year to illustrate the range of successful designs that students might investigate. These actions helped to reinforce the investigative nature of the design process, and implied that students would plan comparative investigations as part of their design.

By encouraging class collaboration and creating formal opportunities to sharing information, Rachel created both the expectation and mechanism by which design ideas
could be shared within the classroom. An implication of this strategy, which augments inquiry through design by providing an explicit mechanism for sharing, is that students may have access to more design ideas over the course of the design project. This could lead in turn to more opportunities to evaluate design ideas — preferably based on empirical evidence — and more potentially interesting questions to explore about the effect of these ideas.

In contrast to Lillian, Rachel took over twice as long to introduce the project; she spoke to the students, with little discussion or student questions, for close to ten minutes. This decision fit with Rachel’s view of herself as more of a project manager than a guide; she intended to fade into the background during the design project and let students work independently on their project. This meant that the project introduction was her main opportunity to explain what was important about the project and to share examples of past work or common problems (e.g. determining when a design fails) that students had encountered in the previous year. As a result, she provided a lot of information and advice up front (e.g. testing procedures, examples of student work, assessment measures) that Lillian had addressed later in the project. In many ways, this introduction reinforces inquiry through design’s approach of using design as an intrinsic motivation for students to engage in inquiry. Her description of how to plan investigations and the examples she gave that supported this were consistent with the ITD approach of structuring designs as investigations. This introduction reinforces what we saw in Rachel’s scheduling of the project; namely, that it aligned well with the view of inquiry through design expressed in the written materials. Students’ introduction to the design project implied a design task that involved comparative investigations.

6.5.4 Touring: Teacher as Project Manager

Rachel viewed her role in the classroom as that of a project manager: someone who helps to set the direction of the project and serves as a resource for students, but tends to stay in the background until needed. Her main goal was to make information and resources available to students so that they could pursue their design projects independently. She also wanted to avoid answering student questions directly, preferring to direct them to information that would help them answer their question themselves.
Compared to Lillian’s approach, Rachel was much more willing to wait for students to ask her for advice or suggestions. 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 the reasons for this approach was her concern 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 forming their expectations for how they would interact with her over the entire year. Rachel explained her strategy in a follow-up interview.

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.

Rachel encouraged students to use each other as resources before resorting to asking her. Since two groups shared each lab table, students were able to easily observe what at least one other group was doing and discuss their ideas. By framing of the design project as a class collaborative effort, Rachel helped to encourage students to visit other tables and ask other students what they were doing.

When students did initiate interactions with Rachel, she tried to avoid making comments about their designs, because she was aware of the impact that her authority would have. Instead, in her project management role, she directed students to resources that could help them answer questions that they had. These resources included material sources such as a local craft store, and information resources such as the table on the board on which groups recorded the results of their design ideas.
Rachel also tried to keep students focused on the project itself, often by responding to student comments and questions in ways that referred to the structure of the project. For example, in this exchange, Lisa, Ellen, and Carrie seek out Rachel because they have tested their design and found it unsuccessful. They demonstrate the test for Rachel, but are unsure what they should do next. Rachel gently prompts them to return to the project and build another prototype, based on their first design.

ELLEN  See, but it doesn’t come back up.

TEACHER  What if you modify your design?

ELLEN  We could change the wires…

CARRIE  We need something that can come back, I guess…

TEACHER  Now you know what your next prototype is going to look like.

Without suggesting specific design ideas, Rachel encourages students to continue designing even though their first design did not succeed. She phrases this as a step forward — “Now you know what your next prototype is going to look like” — rather than a failure. The group proceeds to build and test additional designs.

Rachel also reminded students that she too was learning, and that to answer to their design questions, they would have to test their designs. She was careful to adopt this approach for all student designs, not just those she thought would succeed; she did not want her own biases to discourage students from engaging in a design investigation.

The following exchange illustrates Rachel’s concern about students relying on her rather than working things out themselves. Here, Rachel comes across an ongoing 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 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 Rachel arrives to check on the group’s progress.

TEACHER  Is this your second prototype?

ELLEN  They don’t have any faith in my clay.
LISA 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.

CARRIE 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.

LISA We're replacing the clay with the wire and the rest is going to be the same.

TEACHER Ok.

LISA So we only made one variable.

TEACHER Ok. So are you going to let the clay dry?

ELLEN No. This is -

LISA It doesn't dry. (Pause. TEACHER is looking at design. She smiles skeptically.)

LISA 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...

LISA 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.)

LISA She won't listen to us.

TEACHER Well, it's worth a try. You have one more prototype.

LISA It's not going to work....

TEACHER (Starts to leave, and then returns.) Why don't you guys (LISA and CARRIE) try something else?
Despite her intentions, Rachel’s nonverbal behavior communicated skepticism about the design idea. Lori jumped on this nonverbal cue and Rachel’s status as additional support for her claim that the design idea would not work. Rachel preferred that students resolve these kinds of questions experimentally. She tried to downplay her reaction, encouraging the group to test the design and reminding Lisa and Carol that even if they did not like this design, they would be able to try another. Pushing students to resolve their design decisions experimentally was a common aspect of Rachel’s guidance.

Rachel’s hands-off touring style reflected her own goal of giving students enough autonomy to pursue their own questions. This approach was consistent with her own view of inquiry as a continuum in which greater engagement in inquiry implies more student control of the questions, tests, and procedures that make up an investigation.

So, as to inquiry ... OK, I define it as a continuum where students are coming up with their own process ... and the high end ... their own problem. That really is high end, but it is coming up with process. I think I’m comfortable on the continuum of shifting inquiry from me giving them directions, um, and materials, to them coming up with their own process ... their own procedures ... their own tests .... Um ... giving them time to explore things and not just follow directions ... it’s more inquiry.

...so, I guess that’s three levels — I sort so much out talking about it — so, coming up with their own procedures; coming up with their own ... factors and procedures, tests and procedures; and coming up with their own questions and tests and procedures, perhaps. So, that would be three steps. I need to write that down.

This approach matched her goal of setting an expectation for the school year: that her students could not rely on her to bail them out or give them the right answer.

Rachel reinforced inquiry through design’s focus on design as investigation by pushing students to resolve questions empirically rather than using her own authority to resolve the issue. In this way, she encouraged students with questions about design ideas to plan investigations that would explore those ideas.

From the inquiry through design perspective, one major concern with Rachel’s approach was that, because she chose to make students come to her, there were fewer opportunities
for Rachel to engage in coaching and modeling student inquiry. For example, the observed group in Rachel’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 Lillian’s class. This group built three designs during 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. Had Rachel had more focused conversations with this group, she might have been able to guide student investigation in a more productive direction.

Students had to be aware that they were having difficulty in order to go to Rachel and ask for advice. However, we know from prior work that students have trouble monitoring their own investigations, particularly when engaged in engineering-style tasks (Klahr et al., 1990; Kuhn et al., 1992; Schauble et al., 1995; Schauble et al., 1991b). This suggests that a tradeoff exists between Rachel’s goal of setting expectations for the year and an inquiry goal of scaffolding investigation so prevent students from floundering by pursuing investigative paths that do not lead to comparative data.

In the following discussion, we will revisit student inquiry in Rachel’s classroom, and consider how her teaching strategies contributed to successful engagement in difficult inquiry tasks.

6.5.5 Discussion

Rachel’s approach to teaching inquiry through design shared some elements with Lillian’s, but also differed in a number of ways. How successful were her students at engaging in inquiry in this environment? We saw in chapter 5 that Rachel’s students were able to engage in some aspects of inquiry. In particular, we saw that:

- Students generated several productive questions over the course of the design project. Many of these questions came from other students in the class; some also emerged from controversies within a group about the effect of a particular design idea.

- Students chose to investigate most of these questions in an exploratory manner, planning one-shot investigations that let them know how well the overall design
worked, but didn’t help them to differentiate between specific design ideas. In the case of the focal group, the students belatedly realized that their investigations did not provide them with comparative evidence, and used time outside of class to plan and conduct a comparative investigation to make up for it.

- Students relied on word of mouth as much as empirical evidence to inform design decisions. For example, students were quick to adopt design materials based on word of mouth (“wood is a good material”) and did not require data to support this claim. Often, the evidence available was not sufficient to explain the effect of a particular design idea, because the investigations that led to the evidence were exploratory, or because — as in the case of design ideas written on the board — the evidence for the claim was simply not provided. Students drew on the staging activities as a material source for the design project, but only applied principles from the staging activities in one case.

- Students maintained a collaborative classroom environment, and the competition that is often associated with a strong performance goal focus did not occur. On the other hand, it was not completely clear that the lack of performance goals meant adoption of explanatory goals, as many student decisions led to exploratory investigations, rather than comparative ones.

How did Rachel’s teaching strategies affect student inquiry? Here, I will review the implications of her strategies and relate these implications to classroom practice.

Rachel’s lesson plan reflected the major elements of inquiry through design: staging activities, a design challenge framed as an investigation, and a redesign phase. Of these elements, students seemed to draw the least from the staging activities. Students did succeed in applying principles from one staging activity (Geometric Reinforcement) to their own design and used materials from earlier staging activities in their designs. This result is somewhat surprising given the amount of time Rachel spent on the staging activities compared to Lillian, and suggests that students may need more specific support in order to successfully apply the principles from these activities to the design challenge.

More important to student inquiry was the presence of the redesign phase. On the one hand, the redesign phase was incomplete, because it did not require students to engage in a complete investigation; students had to redesign a single fishing pole based on earlier results. However, the redesign did serve at least two purposes. It provides students with an
opportunity to reason about the data that resulted from earlier design phase, because students had to apply that data to improve their redesign. In addition, the redesign allowed time for reflection (and action) following the initial design. This was particularly important for the focal group, who realized very late on the last day of design that their data did not help them differentiate among specific design ideas. This group was able to plan and conduct a new comparative investigation before the redesign began, and used those results to inform their final redesign. This suggests that in cases where a full redesign investigation is not possible, even a brief redesign phase that allows students to apply earlier results to improve their design is a critical element of inquiry through design.

Rachel’s use of assessment, particularly her innovative use of extra credit to foster collaboration within the classroom, did serve to defuse any competition within the class. While some groups wanted to win the contest, competition was not the driving factor. Students were open to sharing design ideas and materials, and many students visited other groups and lab tables over the course of a period. Students regularly engaged in discussions with the group sharing their lab table as well as other students about the promise or evidence for a particular design idea.

The use of the board as a clearinghouse for design ideas also served to make designs public knowledge. As a result, the focus group, surrounded with materials and ideas, seriously considered far more design ideas than did the group in Lillian’s class.

This collaborative effort culminated with success, as the winning design came out of the observed class, earning each student two extra credit points (and five to the winning group). Although Rachel hesitated to endorse extra credit as a sustainable strategy for promoting collaboration, she did reflect on the underlying strength of the idea: finding ways to reward the class for being a learning community.

... this was the company that had the winning pole. In fact, all three top poles came from this class and they started clapping. And a couple of other people weren’t sure if that was appropriate ... and I said ... yeah ... our company won, we should clap. So, we all clapped .... (laugh). So, they were able to celebrate their success, which was fun too. But, yeah, that was different. I liked that ... I liked what that did. [...] If I can structure something where there is a perk for the class that ... that learns from each other and does something well ... that’s an intriguing idea. [With] cooperative learning
... you could structure roles, you could structure independence ... da da da da, and individual accountability. But this was a little different. This was a class unity, this wasn’t a group unity. It’s a little bigger. So, I liked the way that worked out.

This approach was an excellent example of a teaching strategy that augments inquiry through design and also provides a powerful idea that can inform teaching more broadly.

Rachel presented the design challenge as an investigation, where students would plan comparative experiments to learn about design ideas. In practice, some students engaged in a series of exploratory investigations that did not match Rachel’s expectations and led to student difficulties making sense of their design results. 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 prototypes that Rachel 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 on their own time to build and test three designs that incorporated the materials they had used the previous day — fiber optic cable, wood, and plastic rods — in a comparative way.

How did this disconnect come about between Rachel’s initial introduction of the project and actual student investigation? One factor that played into this was Rachel’s decision to play a more passive role in the classroom. While this decision made sense from the perspective of encouraging students to be more independent and to not look to Rachel for guidance, it also meant that Rachel was not able to track student progress quite as closely. This allowed groups to engage in exploratory investigations without any feedback that this approach might not be appropriate or might lead to poor evidence. These results stand in contrast to Lillian’s approach to touring, where frequent interactions with students allowed her to
provide guidance that helped students to define their design variables and plan comparative investigations.

Obviously, every teacher must make decisions that incorporate a range of teaching goals; for some like Rachel, a project manager role may make the most sense. However, from a strict inquiry through design standpoint, such a passive teaching role does not appear to be effective at supporting student inquiry, because it reduces the opportunities the teacher has to provide feedback for students and scaffold investigation.

Lillian and Rachel took different approaches to teaching what was fundamentally the same unit. We have seen how their decisions and strategies contributed to two very different classroom environments, where students successfully engaged in inquiry in different ways. Now, we will turn to a teacher using a different curriculum: one that focuses on concrete materials instead of composite materials. We will examine the strategies that this teacher — using the module for the first time — employed to support student learning and student inquiry within a design context.

6.6 Doug: Teacher as Troubleshooter

Doug was using the Concrete module for the first time. Doug gave his students considerable freedom to design their own project and assessment measures. Although he was excited about having his students engage in open-ended design, Doug worried whether there was enough time for them to complete the design project. He viewed his role as a troubleshooter who could identify potential design problems before students encountered them.

As in the previous cases, I will review the teaching strategies Doug used to frame the project and support student inquiry, focusing on the implications of his decisions on student inquiry.

6.6.1 Framing the Project: “We’re going to be doing this for eight months”

Doug taught the Concrete: An Infrastructures module over three weeks in the fall. He had not used a Materials World Module before, but was looking forward to trying the Concrete unit and giving his students an opportunity to engage in more open-ended work: what Doug called “inventive thinking.”
I know in my biology classes, we emphasize a lot of linear experimentation. Very tightly controlled, you know, very minute investigations, that don’t lead to much creativity ... 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. All right? So, that was the primary ... that was the reason I wanted to do this.

Because he was using the project for the first time and was not sure what to expect, Doug planned to follow the written materials fairly closely. He used all five staging activities (see Appendix B for descriptions of the activities in the module). Although demanding only five days of class time, these activities were spread over a period of two weeks because some of them involve pouring concrete and waiting for it to cure. Doug’s schedule, which wove these activities in with other curricular activities, was a typical plan for of this module.

Doug chose to use the second of two potential design projects outlined in the written materials. The Concrete module, like all Materials World Modules, offers two distinct design projects. One of these projects is more teacher-directed; it presents students with a predefined challenge, and suggests to the teacher ways for students to evaluate their design. The fishing pole project is an example of the teacher-directed design project in the Composites module.

The second project is more student-directed. Unlike the fishing pole project, where the design goals were effectively defined by the curriculum, Doug challenged his students to come up with their own application for concrete and to define for themselves how they would evaluate the success of their design. Students might choose to design model dams, roadways, pots, or other objects. Although he was concerned that students might have trouble making the many decisions such a project requires, Doug felt that the project offered his students a better opportunity to engage in inventive thinking than did the teacher-directed project that challenged students to design concrete roofing tiles to meet a specified set of criteria.
Doug scheduled five days for the design project. Combined with the staging activities, this meant that he spent close to three weeks on the Concrete module (see Table 6.6). Because of the time needed for students’ concrete designs to cure, five days provided only enough time for a single design cycle. Doug decided that, although a redesign phase would be nice, he couldn’t justify spending more time on the project than he already had. As it was, Doug worried whether his students would be able to complete a single design phase within the available time due to the complexity of the project. Here, he described his initial concerns in a follow-up interview.

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 talking to you, 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.

Doug was using the Concrete module for the first time, and scheduled the project, with the exception of the redesign phase, to follow closely to that of the written materials. From the perspective of inquiry through design, this implied that the lessons from the staging activities would be covered in enough detail to inform later design decisions. On the other hand, the lack of a redesign phase omitted an important element of inquiry through design. This suggests that students will not have time to build on their initial design results or investigate questions that arise from these results.

Doug was aware of some of the implications of dropping the redesign phase, but felt that he simply could not afford to add more time to a unit that already extended to nearly three weeks. In his view, he was using the module for the first time, and he had to do it more or less as written in order to see how it went. In a follow-up interview, Doug described how he would change the project to reduce the time spent on staging activities and increase the time available for design and redesign. He felt he would be able to streamline some activities based on this experience in order to free up time next year.

A final implication of Doug’s lesson plan related to the effect of a student-directed design project on engineering performance goals. Since each group would work on a completely different project idea, there would be no opportunity for direct competition between groups. This suggests that it would be easier for students to focus on developing explanations for their design ideas, since there was less pressure to produce a design that was better than everyone else’s.

6.6.2 Framing the Project: Student-driven Assessment

Doug’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 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, Doug 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. Doug 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 Doug condensed to the five categories that were used for the actual assessment (see Table 6.7).

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

Doug described the benefits he saw in having students become involved in the decision of how they would be assessed.

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.

From Doug’s perspective, it was important to make sure that the assessment criteria were defined early and in a way that students understood. Involving students in generating the criteria was one way to do that. However, this approach is dependent on the teacher to guide students to a set of criteria that are consistent with principles of inquiry through design. As Doug said later, many students are all too willing to define assessment criteria that reward behavior rather than understanding.

In this case, Doug’s “massaging” of the student-generated ideas led to a set of criteria that do not conflict with major principles of ITD. Students are not directly rewarded for design performance; although the “successful production” of a design is mentioned, the focus is on having evidence to support this claim. This suggests that little emphasis would be placed on engineering design goals, allowing students to focus on investigating the effects of their design ideas. The latter three criteria also address, if indirectly, aspects of inquiry through design investigations. However, because the criteria were somewhat vague, it is unclear whether understanding the criteria would help students to engage in inquiry.

6.6.3 Framing a “very complicated... but very simple” Project

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

DOUG 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 had three days to brainstorm and propose their designs, build their molds, and pour their concrete, which then had time to cure over the weekend. On the final day of the project — a Monday — students tested their designs, using tests that they had devised, and then worked on their design logs, which were due at the end of the week. Doug 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 main item that would be assessed.

Doug used the lack of a redesign phase 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.

Doug’s introduction highlights a number of elements of inquiry through design. He explicitly connects the results of staging activities to the design project and posts the data to make it easier for students to use. With this support, student may be better able to apply the results of earlier concrete tests to inform their design. On the other hand, he encourages a more exploratory investigative approach by suggesting that students make multiple prototypes to investigate multiple design ideas. From an inquiry through design perspective, this suggests that students will not be planning univariate investigations, but instead create multivariate investigations that may be more difficult to interpret.

6.6.4 Touring: Teacher as Troubleshooter

Doug’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). As 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, Doug 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. Doug actively toured the room, visiting each group and suggesting ideas. He primarily focused on pragmatic issues surrounding how students would construct molds for the objects, as some of the designs groups came up with — including concrete bowling balls and running shoes — presented serious construction challenges. He often suggested materials and construction techniques to groups to help them build their designs.

Doug also offered critical feedback to groups, particularly early in the project when students were deciding what object they would try to design. For example, when one group
proposed designing running shoes out of concrete, Doug raised several issues concerning
the construction process — as well as the practicality of the design idea — that led students
to abandon shoes and design ornaments instead. Unlike Rachel, Doug was not afraid to
share his opinion of design ideas with his students.

In addition to providing suggestions to help students build their designs, Doug also
reminded students to use the results from previous experiments, displayed on large banners
near the back of the room, to inform their choice of concrete formulations for their design.
But the primary role Doug 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 who's got an idea and they're 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.

By Doug’s own admission, his role in the classroom was geared less to supporting inquiry
than to simply trying to help his students successfully design a product from concrete. This
reflected his uncertainty over using the unit for the first time. As Doug later noted, many of
his fears about whether students could make the decisions necessary to produce a functional
design proved groundless. In the future, he stated, he would be more comfortable and more able to devote time during class towards supporting inquiry.

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.

However, Doug’s approach to supporting student inquiry, viewed strictly from an inquiry through design perspective, did succeed in some respects. For one, Doug took the time, when working with groups, to encourage them to use the data from staging activities to inform their design decisions. Combined with his decision to make sure this data was accessible, students had better access to staging activity evidence than in either Lillian’s or Rachel’s class.

Doug also provided suggestions for design ideas and materials that may have led students to consider design ideas and ask questions about their design that they would not have asked otherwise. In many ways, Doug’s role was simply that of a fellow designer, pointing out potential design flaws and suggesting new ideas. While there appeared to be little scaffolding of comparative investigations, this was consistent with Doug’s introduction to the project, where he encouraged students to build multiple prototypes because they would only have one opportunity to test them.

6.6.5 Discussion

Doug’s experience, as a first-time teacher of inquiry through design and as the teacher of a different module, differed in many ways from Lillian and Rachel’s approach to supporting inquiry through design. In the following discussion, we will revisit the nature of student inquiry in Doug’s classroom, and discuss how his approach to teaching inquiry through design contributed to student inquiry.
In the previous chapter, we saw that students in Doug’s classroom were able to engage in certain aspects of inquiry, although in many ways, their experience was different from students in the two Composite module classrooms.

- Students were able to identify unique design applications for their projects and generate design questions to explore. In fact, groups tended to generate multiple questions to explore during the design phase.

- Student investigations were characterized by a hybrid approach, in which students mixed one or two exploratory designs with a set of comparative design variants. This approach allowed students to explore multiple ideas while also engaging in comparative design, but led to difficulties in explaining results when exploratory designs performed well.

- Although students generated comparative data through investigation, this data was often ignored when exploratory designs outperformed comparative variants. Consequently, students had difficulty using data to explain why these designs performed as they did. On the other hand, students were quite successful applying evidence from staging activities to inform their designs. Many groups used the best formulations from earlier activities as a starting point, and varied these formulations to try to improve on them. This process was aided by the accessibility of the data and the similarity of materials between staging activities and the design task.

- Students were focused on building designs that met their design goals, rather than understanding exactly what contributed to design performance. Although competition was absent from the setting — in part because each group worked on a different design challenge — groups remained focused on improving their designs.

How did Doug’s teaching strategies relate to student engagement in inquiry through design? We will now review these strategies, discuss their implications, and compare these implications to classroom practice.

Doug’s schedule provided substantial time for staging activities and an initial design phase, but no opportunity for redesign. This suggested that students would have time to reflect on the results of staging activities and apply them to the design project. In fact, students were successful at drawing on multiple ideas from the staging activities, using evidence to select
effective mix ratios for their own concrete design projects, and adopting principles of reinforcement to improve their designs. The success of students’ use of evidence from the staging activities rests on more than just providing time for the activities. As we have seen, students in Rachel’s class had substantial time to work on staging activities, but were not as successful as Doug’s students were. I will discuss how Doug helped to make the staging activities more accessible shortly; for now, this case illustrates that given time, staging activities can contribute to student inquiry.

The lack of a redesign phase led to several other decisions made by Doug and his students that influenced the inquiry through design process. Chief among these was Doug’s decision to encourage students to build several prototypes to avoid “putting all their eggs in one basket.” This strategy was a direct result of not having a redesign phase; Doug was encouraging students to make up for the lack of iteration by exploring multiple ideas up front. This approach compromised student inquiry by leading to hybrid investigations.

Doug’s decision to use the student-directed project, rather than the teacher-directed project, also contributed to student inquiry by reducing potential competition between groups. However, it is hard to evaluate how much of a factor competition would have played in the classroom, because students adopted a performance focus anyway, with much of their effort geared towards developing a successful design.

Although student-directed projects may help reduce competition, they also complicate the classroom environment for the teacher, who now must support students working on ten different ideas, rather than ten different approaches to one central idea. This tradeoff contributed to Doug’s choice of a troubleshooting role — a response to fears that students might try to develop ideas (like a concrete running shoe, one initial project idea) that would prove unworkable from the start.

Doug’s approach to assessment involved the students in co-creating a rubric for evaluating the design project. The rubric was consistent with inquiry through design principles of not assessing design performance. Although students were rewarded for producing a design that successfully met the design goals, the rubric emphasized the need to record evidence to support this claim. Unfortunately, the rubric did not explicitly demand explanations for design performance, a central theme of inquiry through design. Student work was
consistent with the rubric: design results were provided, but the evidence did not support specific claims of what contributed to design performance.

It is important to remember that Doug chose to negotiate assessment with his students for reasons other than inquiry through design. He felt it important to engage students in this process so that they would better understand how they would be assessed and could tailor their actions accordingly. The challenge, given this approach, is for the teacher to facilitate the discussion to generate items that relate directly to inquiry through design. At this time, Doug was not focused on supporting inquiry as a primary goal, and the rubric that emerged was consistent with this view.

Doug introduced the design project as a project that grew out of the staging activities. In fact, his introduction began by referencing the results of the most recent reinforced concrete activity, which were posted at the back of the room, and encouraging students to build off this work to build successful designs. In this respect, Doug’s introduction reinforced the connection between the staging activities and the design project. By posting the results from the activities in the classroom, Doug made this evidence easily accessible to students while they worked, which also contributed to its use; students would walk from their lab table to the posters to review the data while they were planning their designs.

Doug’s introduction to the project also planted the seeds for later hybrid investigation by students. His suggestion that students build multiple prototypes to investigate multiple design ideas conflicts with inquiry through design’s principle of structuring the design process as a comparative investigation. It is not surprising that after this introduction, students ended up planning investigations that involved multiple variables and led to difficulties determining the effect of specific design ideas.

Finally, Doug’s role of chief design troubleshooter led him to focus more on helping students to solve logistical problems, such as how to construct a mold for a baseball bat, than scaffolding inquiry. This approach was consistent with his goal of getting through the project and having students construct successful designs. Doug did take advantage of touring to suggest alternative design ideas and approaches to students and used the time to reinforce the importance of using past staging activity results. In this respect, his approach encouraged students to generate new design questions — although they did not investigate
them in a comparative way — and reason with prior evidence to inform design decisions. Both approaches are consistent with inquiry through design.

Doug was aware that he had taken an approach that did not represent inquiry through design as well as it could. Given his understanding of the project before its use, he felt that time was best spent on staging activities and design, and that redesign was a less important element of the project. 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, having now run the module once, he felt that he would be able to find places where he could “cut corners” and find time for redesign by trimming time from some of the staging activities.

Doug’s experience reminds us of several realities of moving instructional innovations into classroom practice. Doug’s beliefs about the particular challenges inherent in design projects and the role inquiry plays in design contexts suggest that we as curriculum developers need to find ways to better communicate the critical aspects of inquiry through design to practitioners. We must also be aware that teachers will adopt a set of goals that reflect their own experience and expectations for their students, and that these goals may not always align with those of inquiry through design. Further, it was clear from talking to Doug in class and during a follow-up interview that he viewed his own practice as iterative in nature, and that he would redesign the module for the following year. We saw in Rachel a teacher who made a series of changes to her own practice to better support student inquiry the second time she ran the project. It is certainly reasonable to expect that Doug will make changes that improve the unit for his own classroom; his discussion of proposed changes aligns well with inquiry through design principles, and Rachel’s experience supports this expectation. Our expectations for how novice teachers enact inquiry through design should be tempered by these realities.

6.7 Discussion: Supporting Inquiry Across Classrooms

We have seen how each of three teachers framed the design project and supported student inquiry throughout the design process. In each of these cases, I have focused on describing the strategic decisions the teachers made within the context of the teacher’s classroom. The purpose of this analysis has been to provide a coherent narrative of each teacher’s approach
to supporting inquiry — given their own goals, their own understanding of their students, and the emergent constraints of classroom practice — and to relate these approaches to my study of student engagement in inquiry described in chapter 5. The discussion that followed each of the cases described the relationship between teaching practice and student inquiry from the perspective of inquiry through design.

In this more general discussion, I will revisit the main goals of inquiry through design: supporting students’ ability to generate productive questions, plan comparative investigations, reason using empirical evidence, and maintain an explanatory focus. For each of these four aspects, I will discuss how teachers effectively supported student inquiry across the three cases. The goal of these analyses is to consider teaching strategies apart from the particular teachers who performed them, and to discuss the benefits and tradeoffs of specific strategies on student inquiry.

The results from chapter 5 serve as a backdrop to these analyses, helping us to focus on instances in which students were successful at inquiry and instances in which they faced significant challenges. How did the teaching strategies we have seen so far relate to student success at inquiry? Would students have been successful under different circumstances?

Sections 6.7.1 through 6.7.4 will address the role teaching strategies play supporting student engagement in the four main aspects of inquiry. (See Table 6.8 for an overview.) In each section, I will present general strategies drawn from these cases that support student inquiry, and explain how the particular teaching strategies from the cases inform these more general approaches. The resulting collection of teaching strategies can be viewed as a supplement to inquiry through design.
6.7.1 Strategies for Supporting Student Questioning

Design projects proved fertile grounds for student-generated questions. The teaching strategies that helped support questions focused primarily on framing the design task to provide time and opportunity for questions to arise.

Make design challenges relevant

Inquiry through design is intended to draw on the intrinsic motivation of a design challenge to engage students in the task, and thus in inquiry. However, not all design challenges will be equally appealing to students. Teachers reinforce this principle by helping to make design projects relevant to students’ everyday lives.

### TABLE 6.8.
TEACHING STRATEGIES FOR SUPPORTING INQUIRY THROUGH DESIGN

<table>
<thead>
<tr>
<th>Inquiry aspect</th>
<th>Strategies for support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asking questions</td>
<td>• Make design challenges relevant</td>
</tr>
<tr>
<td></td>
<td>• Encourage questions that emerge from design testing</td>
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<tr>
<td></td>
<td>• Scaffold the refinement of productive questions</td>
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<tr>
<td></td>
<td>• Let students shape the design project</td>
</tr>
<tr>
<td>Planning investigations</td>
<td>• Support comparative investigations through modeling and coaching</td>
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<td></td>
<td>• Embrace, but constrain, exploration</td>
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<tr>
<td></td>
<td>• Explain the purpose of investigation</td>
</tr>
<tr>
<td>Reasoning using data</td>
<td>• Make empirical evidence accessible</td>
</tr>
<tr>
<td></td>
<td>• Scaffold application of staging activity results to design</td>
</tr>
<tr>
<td></td>
<td>• Model analyses and criteria for evidence</td>
</tr>
<tr>
<td>Pursuing explanatory goals</td>
<td>• Use assessment to reflect and reward explanatory goals</td>
</tr>
<tr>
<td></td>
<td>• Avoid classroom competition</td>
</tr>
<tr>
<td></td>
<td>• Constrain exploration</td>
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Teachers must use their judgement when deciding whether a design task will appeal to students. For example, in one case, another teacher who used the Composites module decided to have students build kites instead of fishing poles, because he felt that his students were more familiar with kites.

Since design challenges serve as anchors (e.g. Bransford et al., 1990) for student investigation, teachers can help shape the task to appeal to students’ personal interests. We have seen Doug use student-directed projects to allow groups to pursue topics that were of particular relevance to them, an approach that aligns with other instructional practices that target personal relevance (Linn & Hsi, 2000).

Although Lillian and Rachel both used fishing pole projects, they introduced the projects in a manner that engaged students in a discussion about the goals and properties of an effective fishing pole. Further, they drew on students’ experience with fishing and fishing poles to help set the context for the project and to begin to engage students in the design process.

Encourage questions that emerge from design testing

The results from chapter 5 show that many of the best questions that students investigated were questions that arose from their own design testing. Often, these results were surprising or controversial, and sparked discussion and interest among the students. Teachers can support this process in several ways. By framing the project to provide time for redesign, as did Rachel and Lillian, teachers create an opportunity for students to explore questions that might arise from design testing. This strategy reinforces an existing component of inquiry through design; one purpose for the redesign phase is to allow follow-up investigation of new design ideas.

In addition, teachers can encourage students to explore these emergent questions. Rachel adopted this approach, constantly encouraging students to investigate their questions empirically.

One tradeoff of relying on emergent questions is that it ducks the question of where students’ initial design questions come from. How might students’ initial investigations be scaffolded in order to generate interesting emergent results? Rachel’s approach, which led students to generate many questions and design ideas, encouraged student exploration in
the early stages of design. It may be that similar approaches that allow students to investigate several design ideas quickly offer a greater likelihood of surprising results and emergent ideas. The challenge, as Rachel discovered, is to structure this exploration in such a way that students can make a clear transition to more investigative practices.

Scaffold the refinement of productive questions

Another important element of teaching practice is to help students refine their own questions about design into productive questions that can lead to scientific investigations. We have seen from Rachel’s classroom that if scaffolding is absent, students may focus on exploratory questions that lead to an unproductive series of investigations. In contrast, Lillian’s regular, structured touring of her classroom allowed her to engage students in substantive discussions about their design ideas, and guide them from these initial ideas to questions that were framed in a productive way.

Teachers can also support student questioning by modeling productive questions. For example, Rachel used a sample design investigation to illustrate her introduction to the design project and process. Similarly, Lillian carried an example of student work around the classroom, showing the design to each group and commenting on how the students had planned an investigation to explore the effect of a core design idea. Whether presented in a whole class setting or in smaller interactions, models for productive questions can serve to support student inquiry.

Let students shape the design project

In different ways, each teacher encouraged students to help shape the nature of the design project. For example, Lillian and Rachel both involved students to deciding which design properties the project would test. Doug went further, allowing his students to negotiate the design challenge itself, as well as determine the properties that would tested. Doug’s students also helped to shape the assessment measures used to evaluate their work.

One reason scientific inquiry is encouraged in science education is that it allows students to help shape the nature of their own investigation (Linn, diSessa, Pea, & Songer, 1994). In so doing, students are able to explore problems that are more meaningful to them. By allowing students to participate in shaping the nature of the project, the teachers provided another
opportunity for students to contribute to posing productive research questions: an important aspect of science that is typically absent from more traditional labs and textbooks (Germann et al., 1996; Jungck, 1991). Allowing students to take ownership of the project is also consistent with Crawford’s findings that group productivity increased in project-based settings where students gained ownership of their own learning (Crawford et al., 1999).

6.7.2 Strategies for Supporting Student Investigations

Inquiry through design encourages students to plan simple, comparative investigations that vary one thing at a time. This approach is intended to shield students from having to interpret empirical evidence from more complex multivariate investigations. However, a tradeoff of this approach is that it constrains the rate at which students can explore new design ideas. Indeed, a great deal of the tension around inquiry through design — which we have seen evidenced particularly well in Rachel and Doug’s classrooms — centers on the balance between open-ended exploration and scientific investigation. Teachers play an important role in navigating this tension.

Support comparative investigations through modeling and coaching

Student success at planning investigations often came after students had been exposed to good experimental design. Models for comparative investigations can come from multiple sources, including staging activities, other students, and the teacher. Although the instructional material provides prompts to help students plan comparative investigations, it does not provide examples that can serve as models for the process.

Teachers can augment inquiry through design and support student investigation by identifying and sharing examples of good investigations as appropriate times. Both Rachel and Lillian used examples of student work to illustrate good experimental design. Of these two, Lillian’s students appeared to be more affected by Lillian’s modeling, because it was offered when students were beginning to struggle with their own design ideas. (Rachel provided an example investigation during her introduction to the project.) Lillian’s work helping students to refine productive questions also contributed to their ability to plan good experiments.
Teachers can also help students to refine their own investigations by coaching them to explain their single variable and explain how their design variants are limited to changes in that variable. This reflects Lillian’s approach to touring, where she visited each group with the intent of eliciting, discussing, and refining their understanding of the central elements of their investigation. Her frequent coaching helped her students to plan investigations that yielded comparative data.

Embrace, but constrain, exploration

The tension between design exploration and scientific investigation is a constant in inquiry through design. Both serve a purpose: exploration leads to a greater variety of potential design ideas, and investigation serves to isolate the impact of a specific design idea. We have seen teachers tend towards both extremes. Lillian drastically limited design exploration, requiring students to identify a variable to explore very early in the design process. This led to successful investigation, but limited the range of questions students had. Indeed, we have seen how one group showed little interest in their initial question, but much more interest in a later question that emerged from their own design results. On the other hand, students in Rachel’s class had the freedom to engage in design exploration for as long as they wanted. We have seen how one group floundered as a result, performing a series of tests that did not disentangle the effects of particular design ideas.

These cases suggest a that middle way, one that embraces design exploration as a tool to generate compelling student questions, but also limits exploration to early stages of the design project. With this approach, teachers become responsible for helping students to make a formal transition from exploration to investigation. A related possibility, which I will discuss in the next chapter, is to introduce a formal exploration phase into the inquiry through design model in order to explicitly embrace, but constrain, design exploration.

Explain the purpose of investigation and redesign

The argument for inquiry through design has been made many times in this document and is described in the teacher’s guide of the Materials World Modules. However, the principles behind inquiry through design — specifically, the goals of design investigations and the value of redesign — need to be communicated to students as well. It was clear from Lillian’s students that various aspects of the nature of the investigation (e. g. “do we have to have a
variable?”) were unclear. Combined with a formal transition from exploration to investigation, a discussion of the nature of the design cycle and the purpose of the redesign may help students realize how they can pursue their investigations over time.

6.7.3 Reasoning Using Empirical Data

Student use of data was perhaps the least effective aspect of inquiry in which students engaged. Difficulties relating the results of staging activities to design ideas and compromised investigations that led to compromised data made it difficult for students to reason about data at all. Teachers who successfully supported student reasoning about design results did so by making empirical evidence more accessible, explicitly scaffolding findings from early activities to the design project, and helping students develop criteria they could use to engage in data analyses.

Make empirical evidence accessible

One benefit of design projects is that testing designs is 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. A critical step that each teacher took was to find ways to make empirical evidence accessible to students. For example, Doug posted results from earlier activities in the back of the room, so his students could easily get up and go check these results. Rachel used a bulletin board approach to allow students to share design results; although quantitative data was not included, the board was visited often by students and the approach could easily be modified to require empirical data. Lillian used design presentations to encourage each group to share their ideas and rationale with other students.

Other researchers have used similar techniques to encourage students to share design ideas. These approaches typically involve asking students to post their designs in a public space to invite comment and critique from other students (Cuthbert & Hoadley, 1998; Holbrook & Kolodner, 2000; Kolodner et al., 1998). The success of these approaches suggests that the principle be reified in the written curriculum, possibly by suggesting formal design reviews or presentations. Such an approach will likely be even more effective if students are asked to share evidence to support their design ideas.
Scaffold application of staging activity results to design

Accessibility related to staging activities as well, where — with the exception of Doug — there was little success prompting students to apply the results of staging activities to the design project. Lillian found herself explicitly asking students to apply the earlier principles relating to bonding and finding resistance to her request. Part of Doug’s success relating the staging activities to the design project came from his introduction. Doug introduced the design project as something that grew out of the earlier activities, rather than a separate task, thereby making a clear connection between the earlier work and the upcoming project.

Once design began, staging activities were mostly ignored by students in Rachel and Lillian’s classes. Had physical evidence from these activities still been present in the classroom, it may have served to spark students to consider the relationship between the activities and design.

Inquiry through design typically includes one design question with each staging activity; the design question is intended to help students reflect on how what they have learned relates to the upcoming design task. Once the design task has begun, students may need to be encouraged to reflect on these questions again in order to scaffold the application of these results to inform student design.

Model analyses and criteria for evidence

A disturbing trend in Rachel’s class was the willingness of observed students to accept design suggestions from other students or Rachel without requiring accompanying evidence. This was particularly surprising because the group did demand evidence to support suggestions from within the group. This suggests that an important teaching strategy would be to establish a set of criteria for accepting design ideas. Such a criteria would also raise the visibility of empirical reasoning within the classroom.

6.7.4 Pursuing Explanatory 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 constraints and optimizes performance, and scientific inquiry goals, which are more concerned with understanding how a particular design idea contributes to design
performance. Although each teacher brought their own approach to this tension, these approaches did share some common characteristics. Chief among these were strategies for encouraging inquiry through explicit assessment measures, downplaying competition, and limiting the role of design exploration in the classroom.

Use assessment to reflect and reward explanatory goals

All three teachers used assessment measures that chose not to reward design performance. Instead of reflecting performance goals, Lillian and Rachel’s rubrics rewarded explanations for design performance that used evidence to support student claims. Surprisingly, basing grades on design performance is not unusual; other teachers who have used the Materials World Modules have done so in the past. However, such an approach may lead students to focus exclusively on performance without reflecting on the effects of specific design ideas or structuring investigations to differentiate design ideas. Rachel reflected on this issue when she discussed her experience the first year she ran the Composites module. At that time, Rachel chose to offer extra credit for the best performing design. Although her assessment rubric did not value performance, the potential for extra credit sparked a competitive design atmosphere among students that encouraged rapid testing of design ideas, rather than careful investigation.

The inquiry through design approach encourages assessment that supports scientific explanation, but does not provide specific examples to support practice. The examples of these teachers serve to augment ITD by reifying this principle in a real-world assessment instrument.

Avoid classroom competition

Although inquiry through design projects are intended to be collaborative ventures, many teachers who have used modules have chosen to inject an element of competition, usually by offering some kind of reward to the top design. Rachel’s use of extra credit is an example of this approach. Encouraging competition within a classroom is generally viewed as a less effective educational approach than involving students in cooperative learning (Johnson & Johnson, 1985). This approach is exacerbated in design settings because competition tends to lead to a fixation on design performance. Rachel’s first year experience reflects this
phenomenon. All this reinforces the importance of the teacher downplaying the competitive aspect of the project.

Rachel’s experience teaching the Composites module for the second year provides a model for limiting competition within a classroom. Rachel’s case demonstrates that competition between classes can be sustained while cultivating a collaborative, open classroom where design ideas are freely shared.

Constrain design exploration

We have seen students make a belated transition from exploration to investigation in Rachel’s class and reviewed the difficulties students face monitoring their own progress during design. In contrast, we have seen how students in Lillian’s class, where design exploration was extremely limited, were more successful at planning and conducting scientific investigations.

These cases suggest that limiting open-ended exploration may serve to help students manage the tension between performance and explanatory goals. As I suggested earlier, one way to do this is to provide an explicit transition from exploration to investigation. Exploration may be embraced as a means to generate design questions, and performance goals accepted over the course of exploration. However, the shift from exploration to investigation brings with it a renewed emphasis on scientific understanding. Understanding how to structure and support this transition may prove to be a critical aspect of teacher support for inquiry through design.

6.7.5 Teachers as Designers of Practice: Balancing Goals

Each of the teachers described here used different strategies to encourage students to engage in inquiry and to build explanations for how different design ideas affected design performance. While all teachers used assessment measures that intentionally avoided placing value on design performance, each found ways to reduce competition and a performance focus. Lillian repeatedly emphasized the importance of designing comparative investigations and used presentations to bring student design ideas into public view. Rachel used extra credit as motivation for collaboration and restructured the design cycle to require
students to engage in comparative investigations. Doug 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, Lillian limited her students’ ability to explore a range of design ideas. Rachel wanted to use presentations to help students share their ideas, but she 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. Doug’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.

These tradeoffs show how teachers must balance classroom and curricular goals as they design their own practice. Each case is different. Lillian’s framing and touring strategies may not be appropriate for Rachel or Doug, and vice versa. What is important is providing examples of what other teachers have done, the goals that drove their decisions, and the nature of student inquiry within this setting.

6.8 Summary

Teachers’ use of innovative science curriculum is complex, and it is unreasonable to expect teachers to adopt whole cloth a new way of teaching or a new kind of student activity. Instead, teachers adapt innovative curricula to their own practice (Cohen, 1988; Kennedy, 1997). This process, as we have seen, means situating curricular material within an already-established classroom culture, and exploring new strategies and approaches that help support student learning during the unit.

From the perspective of the researcher and the designer of new curricular materials, these episodes of adaptation offer more than opportunities to see how teachers change their practice in the face of new instructional frameworks, more than a chance to measure how far these teachers may deviate from the theoretical nature of instruction. Rather, we have an opportunity to see the process by which teachers bring written materials to life — the ways that they support student activity and learning within a specific context.
6.8.1 Learning From Research on Practice

Teacher support for student inquiry is a critical aspect of the classroom enactment. Characterizing teaching strategies as a coherent whole allows researchers and educators to weigh the constraints, goals, and tradeoffs teachers make as they support student inquiry in different ways.

The three teachers whose practice has been documented here engaged in this process of adaptation with inquiry through design. We have seen them apply varying approaches in order to support student inquiry. These approaches were based on their own experience, their expectations for the unit, and their existing goals and expectations for the students in their classrooms. 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.

The strategies that teachers used had a variety of effects on student engagement. Viewed as a whole, one could argue that one teacher’s approach was more effective than another’s. However, my goal has not been to hold up one or more teachers as exemplars of inquiry through design. Instead, I have focused on specific strategies from all three teachers that have contributed to student inquiry. There are several reasons for this approach.

For one, research has shown that teachers often resist new curricular ideas on the grounds that the classroom environment — including the students, the surrounding curriculum, or the available facilities — are either too dissimilar to or more privileged than their own to expect the innovation to succeed (Kennedy, 1997; Krajcik et al., 1998). And indeed, we have seen that classroom context does matter. These teachers’ strategies are to a great extent influenced by their current practice, and we should expect teachers in other classrooms to act in similar ways. Focusing on the successful strategies of teachers in a variety of classrooms provides a broader range of classroom contexts and teacher experience. This range may provide more opportunities for teachers to find promising ways to support inquiry in their own classrooms.

Second, none of the teachers described here can realistically be presented as an exemplar of teaching inquiry through design. Each teacher brought a unique set of goals and expectations to the curriculum, some of which did not align with the principles of inquiry through design. Even Lillian, who co-authored the Composites module and might seem the
most appropriate candidate for this role, presents a number of challenges to being viewed as an exemplar teacher. The case focuses on her teaching a class of less than a dozen students. Consequently, she could provide an exceptional amount of coaching for her students, and she cut short several staging activities because of the time constraints of the unit. Yet, the nature of the coaching Lillian provided, and her rationale for cutting short the staging activities, do provide insight into strategic decisions that impact student engagement in inquiry.

This holds true for Rachel and Doug as well, and suggests that rather than trying to hold up one teacher as a model for inquiry through design, we should focus instead on the strategies and rationales of several teachers, all of whom demonstrated interesting, effective teaching approaches to engaging students in inquiry through design in different contexts.

A final argument for this approach lies in the design of classroom instruction itself. I have taken a stance of viewing education as a design science, one in which we seek to understand the effects of specific instructional strategies — design ideas — in different classroom settings. Holding up one teacher’s classroom, in which multiple instructional strategies have been brought to bear, as the best is remarkably similar to students who seek to build the best design without regard to understanding the effects of individual design ideas. By comparing a series of instructional strategies, the contexts in which they were applied, and the tradeoffs teachers faced in choosing to use these strategies, I believe I have provided a much richer tapestry of design ideas for teachers seeking to integrate design into their own science classrooms.

6.8.2 Integrating Student Learning and Teacher Practice

My goal for this chapter has been to document the strategies that teachers use to support student inquiry through design. 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 with respect to inquiry. Understanding these strategies, and the ways that teachers bring the design curriculum to life in their classrooms, allows us to tailor the inquiry through design approach to better leverage the skills that teachers bring
to the classroom enactment. Documenting these strategies, and the rationale that underlie them, provides a context for their use on which other teachers may draw to decide how appropriate these strategies will be for their own classrooms and goals.

I have presented design as a promising context for engaging students in inquiry, and described how inquiry through design leverages design affordances to try to realize this promise. However, 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 aspect of the classroom enactment. The strategies described here help to illuminate the nature and importance of the role that the teacher plays supporting inquiry through design, and represent another step towards understanding how to support student inquiry in design settings.

In the next chapter, I will discuss how the results of student engagement in inquiry and teachers’ support for student inquiry lead to a reanalysis of the strengths and weaknesses of inquiry through design. More broadly, I will discuss how this work informs the use of design contexts in science education and discuss the role that teachers, students, and the curriculum play in contributing to student inquiry through design.
Chapter 7. Summary and Discussion

7.1 Summary and Review

In chapters 5 and 6, I have presented evidence that students successfully engage in challenging aspects of scientific inquiry and that teachers support successful student engagement in a variety of ways. These results suggest that inquiry through design (ITD), a framework from supporting student inquiry through design projects, can be an effective context for scientific inquiry.

In this chapter, I will review this research and characterize the nature of student inquiry within design contexts. I will summarize how inquiry through design supports students’ ability to engage in challenging aspects of inquiry. I will discuss how different elements of inquiry through design contribute to student inquiry and relate to approaches used by other researchers in science education. I will discuss how what I have learned informs the nature of inquiry through design itself, and I will propose changes to inquiry through design to better support student inquiry. Finally, I will discuss the implications of my work on the role of design within science education and on the value of classroom-based studies as a means to document student inquiry and teacher practice.

7.1.1 Where We Have Been

In chapter 1, I raised an important issue: the need to better support student inquiry within science education. Recent research and science education reform efforts have highlighted the importance of providing opportunities for students to engage in scientific inquiry, an authentic approach to learning science. For such opportunities to be successful, however, students need support in the process of doing science.

I have reviewed research that has identified several obstacles to successful student inquiry. These challenges relate to particular elements of scientific practice, including the ability to ask questions that lead to productive investigation, plan investigations that tease apart the effects of suspected causal factors, reason using evidence to identify causal factors and support scientific claims, and maintain a focus on constructing explanations for scientific phenomena.
I have presented design as a promising context in which students may engage in inquiry. I have described how design contexts afford opportunities for students to address these particularly challenging aspects of doing scientific inquiry. Although aspects of engineering design — such as the ease with which empirical evidence can be generated — are promising, design also raises a number of issues that must be addressed for design projects to be successful means of supporting scientific inquiry. Chief among these is the apparent tension between the performance-based goals of design and the explanatory goals of scientific inquiry.

In chapter 2, I presented inquiry through design, a model intended to address these concerns while leveraging design’s affordances for inquiry. Inquiry through design consists of several elements that help support student inquiry. Staging activities that precede the design project model scientific investigation for students and provide background information that students may apply to their own designs. The engineering design challenge itself is crafted to leverage design affordances, presenting students with an authentic, open-ended task that supports multiple design ideas and generates empirical evidence. The design project itself is structured like a scientific investigation, aligning the design process and the inquiry process to help students to successfully investigate specific design ideas. Finally, opportunities for redesign allow students to apply what they have learned to improve or change their design. Iterative design also provides students with multiple opportunities to plan and conduct investigations of their own design ideas.

Inquiry through design is itself the product of an iterative design process. It has been refined over the course of developing and pilot testing the Materials World Modules, a series of two week, project-based curricula that focus on specific topics within the field of materials science. Two of these curricula, the Composites Module and the Concrete: An Infrastructure Module, are described in chapter 2 and Appendices A and B.

To assess the effectiveness of ITD, I have focused on two main research questions. These two questions reflect an interest in examining the effect of an instructional innovation within realistic classroom contexts.

- What does student engagement in inquiry through design look like, and how successfully can students engage in challenging aspects of scientific inquiry?
• How do teachers support student inquiry within this setting, and what specific strategies appear to contribute to student inquiry?

Each question explores student success across the four challenging aspects of inquiry that I raised in the introduction: asking questions, planning investigations, reasoning with evidence, and pursuing explanatory goals. Because written curricula undergo a process of translation when they are enacted in classrooms, my questions focus on documenting the nature of inquiry and design within a classroom context in order to assess how the taught curriculum engages students in inquiry through design.

In chapter 3, I described three studies of inquiry through design that involved three different high school teachers — Lillian, Rachel, and Doug — and were based in authentic classroom contexts. Each classroom provided rich examples of student inquiry and teacher practice, from which I constructed three narrative cases of student inquiry through design. Each case followed one or two groups of students in detail as they worked through the design project, providing insight into the nature of student design decisions and student inquiry within a design context. In Lillian’s classroom, Sarah, John, and Kathy worked together to investigate how to use telephone wire to reinforce their model fishing pole design. In Rachel’s classroom, Lisa, Ellen, and Carrie explored the effect of several design materials on their fishing pole design. In Doug’s class, where students pursued their own design challenges, Beth and Luke designed miniature cooking pots out of concrete, while Lois and Larry chose to build bocce balls. Condensed descriptions of each narrative case are presented in chapter 4.

In chapter 5, I presented analyses of four aspects of student inquiry. By following groups of students over the course of their design project, I was able to describe and assess how students engaged in difficult aspects of inquiry while meeting the goals of the design project. I presented results indicating that students could pursue multiple aspects of inquiry within a design context. Further, the design challenges proved to be highly motivating contexts for student investigation. When students had difficulty engaging in inquiry, it was often due to their adoption of design goals that led to more exploratory investigations that did not yield comparative data.

In chapter 6, I turned my attention to teachers and the strategies that they used to structure and support inquiry in the classroom. By examining three teachers who represent a diverse
range of expertise teaching with inquiry and design, I was able to describe a series of strategies for supporting student inquiry in the context of specific classroom goals. Some of these strategies reinforce existing aspects of inquiry through design, while others offer innovative new approaches to incorporating inquiry into a design context.

The remainder of this chapter summarizes my findings and places my work within the broader context of science education and other project-based efforts to support scientific inquiry. In section 7.2, I will discuss what we have learned of the nature of student inquiry in design settings and the ability of inquiry through design to support student engagement in inquiry. We will look closely at what worked, what didn’t, and the degree to which these successes and missed opportunities can be attributed to the written materials, the teacher, and the students themselves. In section 7.3, I will discuss the implications of my work on science education research and practice, focusing on contributions to understanding the role of design in science education, how inquiry may be supported in varied contexts, and how teachers may incorporate new contexts into their own practice. In section 7.4, I will turn to the iterative design of ITD itself and consider the implications of my research on ITD as a model of instruction. Finally, in section 7.5 I will discuss future directions for this work and its contributions to recent efforts to scale innovative science education from small, highly scaffolded classrooms to more typical school settings.

7.2 The Nature of Student Inquiry in Design Contexts

There are many obstacles to successful student engagement in inquiry. Students need support to generate and refine productive questions that lead to scientific investigation (Barron et al., 1998; Blumenfeld et al., 1991; Scardamalia & Bereiter, 1992). Once focused on a particular question, students need support to plan investigations that will adequately test student theories or inform new explanations (Klahr et al., 1990; Kuhn, 1993). Students need support to relate empirical data to specific claims (Kuhn, 1993; Kuhn et al., 1992; Linn, 1992a). Finally, successful engagement in inquiry is predicated on a goal of pursuing explanations. Student need to adopt explanatory goals rather than focusing on producing specific outcomes or improving design performance (Barron et al., 1998; Kuhn & Phelps, 1982; Schauble et al., 1995).
In chapter 5, I showed how students were able to engage in many of these challenging aspects of inquiry. Student inquiry in design contexts was shaped by many factors, including the nature of the curriculum, the role of the teacher, and the students themselves. The core elements of inquiry through design — staging activities, the design challenge, design investigations, and iterative redesign — were represented in the curricular structure of the Materials World Modules and provided opportunity and support for student inquiry. Teachers also shaped the nature of inquiry through design in the classroom. Their framing of the design project, along with the support they provided during the project, served to reinforce and augment inquiry through design.

In this section, I will review the methodology I used to document student inquiry and characterize the nature of student engagement in these challenging aspects of scientific inquiry. I will also discuss how specific elements of the inquiry through design approach, along with specific teaching strategies, contributed to student inquiry. Finally, I will summarize these findings in terms of inquiry through design’s overall support for student inquiry and its relationship to existing research on design- and project-based approaches in science education.

7.2.1 Documenting Student Inquiry Using Narrative Cases

I began this dissertation with the goal of documenting the nature of student design in inquiry contexts. To achieve this, I adopted an approach that emphasized close observation of classroom practice, following groups of students over time to generate a rich narrative of the process of student inquiry through design.

There are two main strengths of this approach. First, it provided thick description of student action from the perspective of design and design investigations. The depth of the cases provided enough context to support interpretation of different aspects of student inquiry that occurred over the course of the design project. I will review these results in the next section.

Second, my approach addresses recent calls to examine practice in realistic classroom settings (Krajcik et al., 1998). My work acknowledges the roles that the teacher, the students, and the instructional materials play in shaping the nature of classroom practice (Ball & Cohen, 1996). Although the main focus of my research has been to show how teachers and
the inquiry through design framework contribute to student engagement, the narrative cases also document instances in which students and the curriculum shaped teachers’ actions. Indeed, a fundamental assumption of my research is that teaching practice changes over time as teachers reflect on their own practice (Schön, 1987). My approach shows how teachers’ approaches to teaching with design have been shaped by prior experiences in the classroom and prior interactions with students.

As researchers and educators continue to scale science education innovation from hothouse settings to more widespread use, it becomes more and more important to study student learning in typical classroom environments. The methodologies I have used here inform this research by providing a means to document student engagement in inquiry and capture how classroom practice is negotiated within — and how curricular reform adapts to — specific classroom settings.

7.2.2 Asking Questions About Design

My research has shown that students engaged in design projects can generate productive questions about their designs. These questions in turn drive student investigation of the relationship between design ideas and design performance. The questions students generated were particularly valuable because they were unique, personally relevant, and sought to relate structure to function.

Because groups generated questions about different design ideas, each group’s investigations were unique. This allowed students to pursue their own personally relevant questions rather than a single question as a class. Student questions were personally relevant because students speculated about their own design ideas and how different materials would effect their own designs. Personal relevance is an important aspect of science learning contexts that researchers argue encourage student motivation and help students to integrate their scientific understanding of science in the real world (Edelson, 1999; Linn & Hsi, 2000).

A similar concept is the driving question. Driving questions serve as important contextual anchors from which students engage in the investigation of related sub-questions (Blumenfeld et al., 1991; Crawford et al., 1999). Typically, driving questions are situated in authentic problems or issues that students can relate to their own experience. In a sense, the
task of design can be viewed as driven by an overarching “driving question.” The design challenge spawns a series of more specific design questions that are tied to specific design ideas.

Within each class, students generated a variety of design questions. These questions typically explored the relationship between specific design ideas and specific design properties. For example, students in the Composites module explored how certain design materials, such as wooden skewers or strands of telephone wire, contributed to the strength and stiffness of the overall design.

An important characteristic of students’ questions was that they explored the relationship between design structure and design function. Understanding relationships between structure and function is key to understanding what affects design performance; questions that focus on non-functional characteristics, such as color, do not inform students’ causal understanding of design (Hmelo et al., 1997; Sadler et al., 2000). Investigating functional relationships can directly inform iterative design efforts and provide empirical evidence to support claims about design performance.

Another important aspect of student questions is that they were speculative. These questions, which often begin with the phrase “what would happen if,” demonstrate the students are able to generate the kind of knowledge-based questions that lead students to engage in sustained investigation to improve their own understanding (Scardamalia & Bereiter, 1992). Design encourages this kind of questioning because design ideas naturally lend themselves to speculation over their effect. One minor concern is that often, students’ initial design questions were very open-ended. Students asked questions such as “how will this idea affect my design” rather than making predictions that tied design ideas to specific design properties such as strength. However, once students began empirical testing, the results of these tests often sparked new questions and ideas that were more closely tied to specific functional properties.

Another concern about the nature of students’ design questions is that they may not lead to the investigation of fundamental scientific principles within the subject domain. Design-based curriculum that has attempted to support student inference of basic scientific principles have focused on domains such as simple levers, where the visible structure of the design can be causally related to design performance (Penner et al., 1998; Sadler et al., 2000).
In materials science, however, the visible structure of the design does not always inform causal explanation. For example, the visible structure of steel and wood rods to do lead to causal explanations for why steel is stronger and stiffer than wood; the explanation for the difference in properties is rooted in the molecular structure of the materials.

However, successful inquiry need not uncover fundamental scientific principles. Many projects that incorporate design do so to engage students in the task and rely on staging activities or pre-existing investigations to introduce key scientific principles (Barron et al., 1998; Cuthbert & Hoadley, 1998; Kolodner et al., 1998). Inquiry through design also relies on staging activities to introduce key principles, but differs from these approaches by scaffolding scientific investigation as an integral part of the design process.

Fundamentally, scientific inquiry is driven by a search for better explanations for phenomena in the world. Within a design context, students pursue explanations to understand why certain design ideas lead to better design results, thus informing ongoing design efforts. Inquiry through design succeeds because students engaged in ITD are able to generate unique, personally relevant questions that lead to investigations that uncover previously unknown relationships between design ideas and design performance.

My work has demonstrated that the design project itself is a powerful source of student questions. Many meaningful student questions emerged from surprising empirical results. As in other inquiry-based environments, ITD prompts students to make predictions prior to testing. Surprising results that contradict student predictions then serve as a means to prompt students to investigate further to explain the difference between prediction and result. Fostering prediction is a common strategy employed in other project-based environments (Barron et al., 1998; Linn & Hsi, 2000). It is particularly powerful here because of the ease with which students can generate empirical results.

Student questions were also driven by controversy. Controversy, and the methods intended to resolve disputes over controversial ideas, are hallmarks of science. Recent efforts in science education have begun to use controversy to reinforce the idea that science is a dynamic discipline and that scientific ideas do not simply emerge, but are refined over time through experimentation and argument within the scientific community (Edelson et al., 1995; Linn et al., 1999b). We have seen that within design contexts, controversies over
specific design ideas can spark student investigation, as students seek to prove each other wrong.

While the design context itself proved the main source for student questions, teachers also contributed by encouraging students to investigate their own questions and helping students to refine their own questions. Interestingly, the three teachers studied did not tend to suggest questions for students to investigate. They recognized that students were generating their own questions and focused their efforts on refining these questions so that they would lead to better investigations. This role is consistent with that taken by teachers in other project-based settings, in which a general research area is proposed, but teachers work with students to identify questions within the subject domain that they will pursue (Crawford et al., 1999; Polman & Pea, 1997).

7.2.3 Planning Design Investigations

Students’ design investigations were characterized by two classes of investigation. Students engaged in exploratory investigation by building and testing individual designs, often merging several design ideas at once in order to see if the ideas improved design performance. In contrast, during comparative investigation, students limited the number of design ideas, building and testing a series of design variants to understand the impact of a particular design idea.

Exploratory and comparative investigations reflect different approaches to scientific inquiry. Exploratory investigations, where students seek to “screen” a large number of design ideas within a short period of time, are a kind of heuristic that can be used to identify a particular set of design ideas that may be pursued in greater depth. In design settings, where the number of potential design ideas is very large, such heuristics are an important part of design and inquiry (Beveridge, 1950; Bucciarelli, 1994).

Comparative investigations allow students to closely examine the effect of particular design ideas. By carefully controlling the changes among design variants, students can generate comparative evidence that will support claims about the effect of these ideas on design performance. This kind of investigation is more typical of scientific inquiry, and can also occur within a design context.
My research shows that students demonstrated an important ability to plan and conduct investigations that resulted in empirical data. Students’ ability to engage in self-directed investigation was a concern of teachers as well as researchers, and their success in moving from asking an initial design question to producing empirical evidence shows that the structure of design investigations can serve as an effective scaffold for this aspect of scientific inquiry.

Within the three classrooms, I have shown how students tend to plan exploratory investigations as they search for powerful design ideas that can improve their designs. These investigations often consist of rapid, qualitative testing, as when students in Rachel’s class evaluated a series of design materials by picking them up and bending them by hand, gauging their relative strength and stiffness. Exploratory investigations often arose from speculative design questions that sought to investigate how one or more design ideas affect overall design performance.

These results are consistent with past research on the relationship between exploration and comparison in design tasks (Hmelo et al., 2000; Schauble et al., 1991b). Exploration and comparison are two different aspects of inquiry. Particularly within project-based domains, providing time for exploration — what Kolodner terms “messing about” — is an important aspect of inquiry (Kolodner et al., 1998). Schauble in particular has argued that the transition from an exploratory engineering model of experimentation to a comparative scientific model of experimentation is more effective than expecting students to immediately engage in comparative investigation (Dewey, 1913; Schauble et al., 1991b).

From this perspective, student exploration is an appropriate early phase of inquiry. However, students’ persistence in engaging in exploration throughout the design project suggests that stronger scaffolding is needed to facilitate this transition from exploration to comparison. For example, Lillian’s coaching of student planning helped her students to plan comparative investigations during their first design iteration, while students in Rachel’s class, who had more autonomy, engaged in several rounds of exploratory design before focusing on a specific comparative investigation.

Persistent exploration is a concern because the nature of students’ investigations has a direct impact on the nature of empirical evidence that students use to reason about their designs. Because exploratory investigation does not produce comparative data, students will not
have evidence to support claims about the effect of specific design ideas. For example, after students in Rachel’s class pursued three iterative designs, they realized that their results did not help them to tease apart the effect of the more than five design ideas that they had used over the course of the three iterations.

Inquiry through design scaffolds comparative investigation through written prompts in the student edition and in the design log sheets included with the module. However, in the three classrooms studied, students either did not have access to these prompts or did not attend to them. This meant that the teacher was the primary source of support for student investigations.

The importance of providing coaching for students engaged in open-ended scientific investigation has already been established (Collins et al., 1989; Crawford et al., 1999; Hammer, 1997; Kuhn, 1993). Teachers who adopted a coaching or mentoring role were better able to guide their students through the process of planning good comparative investigations. For example, we saw that Lillian’s frequent coaching helped her students to generate comparative design investigations. Her role as guide enabled her to have more frequent student interactions than did Rachel, and her focus on supporting student investigation led to more meaningful interactions — from the perspective of inquiry — than did Doug’s role as a troubleshooter and fellow designer.

These results suggest that inquiry through design should encourage teachers to adopt more proactive roles in the classroom and to actively coach students through the planning of comparative investigations. However, this approach presumes that such a role will not interfere with teachers’ existing classroom goals. In Rachel’s case, there was a tradeoff: she could not provide more proactive coaching as long as she held a goal of developing her students’ autonomy.

By explicitly raising the importance of coaching student investigation, ITD can help teachers to be aware of the tradeoffs that they face as they adapt design contexts to meet their own classroom goals. Understanding these tradeoffs may be particularly important for first-time teachers, who do not yet have experience teaching in design contexts.

Redesign may also contribute to student investigation by providing multiple opportunities for both exploratory and comparative investigation. We have seen that students in Doug’s class who did not have the opportunity to redesign engaged in a hybrid form of
investigation. The nature of their investigations reflected student interest in pursuing speculative design questions even while planning comparative investigations. If ITD is to support both initial exploration and later comparison, iterative redesign becomes particularly important, because it provides students with the means to plan different kinds of investigations over time and would support a transition from exploration to comparative investigation.

7.2.4 Reasoning About Design

Students used empirical evidence from staging activities, their own design testing, and other groups’ design testing in various ways. The strongest use of evidence to reason about design ideas was found in students’ use of their own design results to inform later design efforts. Here, students drew on empirical results to argue for the role of specific design ideas, while surprising results sparked new lines of inquiry and focused investigation on specific functional properties.

Students were much less consistent using the scientific principles and evidence from earlier staging activities to inform their design. Specific scientific ideas that were embedded in these activities, such as the importance of bonding in constructing composite materials, were ignored, indicating that students either failed to understand the original principle or failed to apply the principle to a new design context. In part, this may have occurred because staging activities preceded, and were therefore somewhat divorced from, the design project itself. Other research groups have addressed this concern by weaving staging activities throughout the design project (Kolodner et al., 1998; Krajcik et al., 1999). In these approaches, staging activities are introduced as they are needed to inform the larger project, and students engage in reflection to tie the principles behind the staging activities to the project goals.

Students were also much less consistent in evaluating the design claims of others. Here, students often accepted claims of effective design ideas at face value. In some cases, students faced with claims that directly contradicted their own findings accepted the competing claim without demanding supporting evidence. Although this may imply a certain degree of trust among fellow students and designers, it also suggests that students did not have a model for critically evaluating design claims.
Although students were able to construct arguments for the effectiveness of specific design ideas and use evidence to support their own claims, student claims tended to relate structure to function without providing an underlying causal explanation for why a given relationship existed.

Successfully identifying these relationships is an important first step towards constructing more complete explanations. This difficulty in developing causal explanations may be an issue that relates more to the subject domain of materials science than it does to inquiry through design as an instructional framework. The nature of materials science does not lend itself to causal explanations that may be inferred from physical structure. For example, it is difficult to explain why steel is stronger and more stiff than wood, although it is possible for students to determine empirically that this relationship exists.

Other design-based projects have successfully scaffolded student inference of causality in physical domains such as simple levers, where the visible structure of the design is closely related to design performance (Penner et al., 1996; Sadler et al., 2000). Materials science, which places a strong focus on understanding the fundamental properties of materials, may be less well suited for this kind of investigation.

Students’ ability to reason using empirical evidence was also constrained by the nature of their design investigations. We have seen in the previous section that students often engaged in exploratory investigation. Evidence from exploratory investigations provides feedback about overall design performance, but often does not inform reasoning about the effect of a specific design idea. The relative lack of comparative investigations, excepting settings where investigation was highly scaffolded, meant that students lacked the opportunity to reason about design ideas in a comparative way because the data simply did not exist or was ignored.

In some cases, students were aware that their evidence did not support claims about the effect of specific design ideas. The observed group in Rachel’s class came to this realization, which prompted them to plan a new comparative investigation instead. In other cases, exploratory evidence distracted students from more comparative results. In Doug’s class, we saw how students planned hybrid investigations that combined exploratory and comparative elements. When students tested their designs, they focused their attention on
the better-performing exploratory results, and ignored the comparative data that would have informed their understanding of specific design ideas.

In either case, this suggests that ITD must first scaffold investigation so that students will have the opportunity to reason about their designs in a comparative way. This point is particularly important in design contexts, because design projects are dependent on student investigation to generate empirical data.

Where students were able to reason successfully about their designs, teachers played an important role. Teachers used presentations, posters, and blackboards as vehicles to help students share and access evidence about design performance. Doug’s posting of staging activity results made it easier for his students to apply these findings to their own designs, because the data was always at hand. Students’ design results can be made more accessible as well, particular to students in other groups. Students need to share evidence as well as conclusions for other groups to be able to reason about their findings. Formal presentations like those in Lillian’s classroom and pin-up boards similar to those used by Kolodner et al. (1998) may place more scientific evidence within reach of student reasoning.

Technological support tools can also contribute to this process. Existing investigation support tools like the Progress Portfolio may allow students to more easily organize and annotate their own work (Edelson, 1999; Loh et al., 1998). Design storyboards such as those used by Sadler may help students to organize their ideas, particularly if the storyboards are used and updated throughout the project rather than solely at the end (Sadler et al., 2000). Wireless handheld computers that organize student results may facilitate the sharing of evidence, as students could simply “beam” data to other groups to provide evidence for design success (Soloway et al., 1999).

However, an important caveat here is that the design challenges recommended by ITD are fundamentally hands-on engineering tasks that are not done on a computer. This means that technological support tools are not intrinsically tied the task, as they would be if students were conducting an investigation using a computational simulation. The challenges educators face prompting students to attend to technological support tools are similar to those of prompting students to attend to written support tools like black line masters or worksheets.
Another scaffold that may help students to engage in better reasoning about their data is to model for students how to critique design evidence. Although ITD models the process of planning comparative investigations, it does not explicitly model how to use data to evaluate design claims. Providing opportunities similar to those in the Knowledge Integration Environment, where students are explicitly asked to critique scientific claims, may help students to better understand how to support claims about design performance (Bell, Davis, & Linn, 1995).

7.2.5 Pursuing Explanatory Goals

 Providing students with motivating contexts for learning is an important aspect of learning environment design (Bransford et al., 1990; Edelson, 1999; Linn & Hsi, 2000; Schank, Fano, Bell, & Jona, 1993/1994). A strength of design contexts is that they can be highly motivating. However, by placing student inquiry within a design context, inquiry through design encourages students to adopt design goals as well as more explanatory goals.

We have seen that students quickly adopt design goals and become highly motivated to improve design performance. We have also seen that in some cases, these design goals are so strong that students continue to explore when they know that they should be planning comparative investigations. This suggests that students have difficulty maintaining design goals and explanatory goals at the same time.

Despite the resilience of design goals, students were able to pursue explanatory goals. However, students typically did not adopt these goals unless they had substantial teacher guidance, as was the case in Lillian’s classroom, or they were faced with surprising or controversial evidence. Once students encountered unexpected results, they began to plan investigations to make sense of their findings.

In this way, the balance between design goals and inquiry goals represents a transition that mirrors exploratory and comparative investigation. Design goals, reflected in the nature of students’ investigations as well as their perceived goal of producing a better design, arise naturally from the design challenge itself. Explanatory goals, which lead to comparative investigation and careful comparison of empirical results, typical arise in students once they observe unexpected design results.
The ease with which students adopt and pursue design goals suggests that it is important for teachers to actively encourage explanatory goals. We have seen evidence of teacher strategies for limiting competition and fostering explanation across all three classrooms.

For example, we have seen how students strive to continually improve their design. However, in some cases, this motivation can turn into competition, leading students to focus too much of their attention on design performance instead of understanding the effect of specific design ideas.

Lillian, Rachel and Doug all framed the design project in ways that limit direct student competition. (Although Rachel fostered competition between classes, she was careful to encourage collaboration within each class.) Their strategies included the use of assessment to downplay design performance and reinforce collaboration, group presentations to encourage the sharing of design ideas, and individualized design projects to discourage comparison across groups.

While competition may “spice up” the project and provide motivation, the cases here suggest that the design challenge alone provides suitable motivation. Students are deeply engaged in the task. The risk of layering competition on top of design is that students will focus even more closely on the performance goal, to the extent — Rachel described this occurring the first year she used the Composites module — of refusing to share design information with students or the teacher.

These teaching strategies have immediate implications for the current written materials, which phrase the design challenge in a competitive manner. They suggest that the design challenge be presented in a more neutral way, as a “test against nature,” rather than as a competitive process (Sadler et al., 2000). Such an approach would allow teachers to phrase the design task in their own terms, and to use assessment measures that reinforce the inquiry goals of the task.

In addition to downplaying competition, it is important for teachers to explicitly value explanation in order to encourage students to adopt explanatory goals. Rachel’s story of competition running amok is an important lesson. In two of the three cases seen here, students who knew they were being assessed purely on investigative and explanatory grounds persisted in exploratory design. Imagine if design performance actually determined their grade! Each of the three teachers here constructed an assessment rubric that valued the
process of investigation rather than overall design performance. Each teacher also spent time in class discussing the rubric with students, in order to help them understand what was expected of them.

The written materials can provide examples of assessment rubrics and should provide guidelines for assessment; in fact, the teacher’s editions of the Materials World Modules make these recommendations, but lack specific examples that illustrate how students respond to different assessment approaches. As I mentioned earlier, rich narratives of classroom practice, which include example rubrics as well as examples of student work, may help teachers to better understand the tradeoffs of particular assessment approaches with respect to student engagement in inquiry.

The ITD approach presumes that students could adopt and pursue design and inquiry goals in parallel as students worked on their design projects. My research shows that open-ended design is a powerful motivational context in which students have difficulty pursuing design goals and explanatory goals simultaneously. Students need stronger support, particularly teacher support, to adopt explanatory goals. In light of these findings, it would seem that ITD might have more success supporting a transition from design goals to explanatory goals as part of a process of moving from exploratory investigations to more comparative ones. In section 7.4, I will discuss how ITD might support such a transition.

7.3 Implications of Inquiry Through Design for Science Education

The primary goal of this dissertation has been to examine how to scaffold a promising design context to support student engagement in scientific inquiry. The research I have presented paints a rich portrait of design in classroom practice, examining the challenges and rewards for students and teachers who engage in design.

I have described how students engage in inquiry through design and the ways that the curriculum and the teacher contribute to supporting successful student inquiry. I have discussed some of the concerns facing inquiry through design, particularly issues surrounding exploratory design and the need to scaffold students’ explanatory goals.

Here, I will discuss how inquiry through design, as an instructional approach, relates to other theories, strategies, and frameworks that researchers and teachers are using to support design- and project-based inquiry in science education. I will also address the implications
of my research on science teaching. I will discuss how narrative methodologies can shed
light on teaching goals and teaching practice, and suggest an approach for supporting
teachers as they integrate new curricular materials into their own practice.

7.3.1 The Role of Design in Science Education

The success of the inquiry through design approach provides support for the claim that
technological design projects have a place in science education. This issue is not particularly
contentious, as the National Science Standards include standards for technology design and
several other research groups have been investigating design contexts as contexts for
learning (Barak & Raz, 2000; Cuthbert & Hoadley, 1998; Hmelo et al., 2000; Kolodner et al.,
1998; NRC, 1996; Penner et al., 1998; Sadler et al., 2000). However, design has been primarily
positioned as a means to teach content. Addressing scientific inquiry through design is more
problematic, because it must address students’ tendency to adopt engineering goals, rather
than explanatory goals, over the course of the design (Hmelo et al., 2000; Schauble et al.,
1991b). My research suggests that with suitable scaffolding, students can pursue inquiry
within a design context. This allows educators to draw on the affordances of design within a
controlled setting to motivate and support elements of student inquiry.

Further, my work speaks to an ongoing conversation within science education about the
criteria for effective design challenges. It strengthens the case for hands-on design where
students build and test objects to evaluate their performance (Sadler et al., 2000). Students
must design functional, rather than appearance-based, objects (Hmelo et al., 2000). And
design works best in subject domains where students can infer scientific principles through
close observation and investigation. My findings suggest that educators carefully select
content domains for which design investigations can yield causal explanations for design
performance.

The support for student inquiry that is embedded within ITD also informs ongoing efforts
to better support student design investigations. Researchers and educators who use design
to engage students in inquiry should be aware of the potential obstacles that students face
and the scaffolds that help students to succeed. We have seen that students often pursued
exploratory investigation, made errors of false inclusion when reasoning about designs, and
neglected to consider evidence, from other groups and earlier activities, that could have informed their design decisions.

Inquiry through design provides a model for using iterative design as a scaffold for student inquiry. In this respect, it extends prior uses of design to learn about scientific content to include the use of design to support engagement in a basic scientific process. The implications of this work extend beyond the use of design in science classrooms to inform means by which educators can support student inquiry in project-based settings.

7.3.2 Supporting Inquiry in Science Education

An important challenge to supporting inquiry is providing a motivating context in which students will want to engage in scientific practice (Edelson, 1999). Others have proposed a variety of means for motivating student inquiry, including video-based anchors that capture students’ interest, driving questions that lead students to generate their own questions, and role-playing scenarios that encourage students to solve a particular problem (Blumenfeld et al., 1991; Schank et al., 1993/1994; Vanderbilt, 1990). Design has also been presented as a means to support student engagement, both within larger instructional frameworks (Cuthbert & Hoadley, 1998; Schank et al., 1993/1994) and as an activity of its own (Kolodner et al., 1998; Sadler et al., 2000).

My work demonstrates that engineering design contexts can be very successful at motivating students to engage in the process of learning science. In some ways, design contexts may be too compelling; we have seen that students need support to maintain explanatory goals while trying to improve design performance. However, with appropriate scaffolding, design contexts offer an excellent means to engage students in project-based work.

In design projects, educators must take care to focus students on explanatory, rather than performance, goals. A similar concern faces project-based science. Students may become distracted by the form of their work rather than focusing on understanding the content of their work. For example, students may spend too much time on the appearance of a final report or multimedia presentation. The strategies that teachers have used to limit performance goals, including the use of assessment and student presentations to focus students on evidence and understanding, apply equally well to inquiry-based project settings.
My work suggests that this tension may be resolved through a transformative process, rather than through an attempt to completely remove one set of these goals. We have seen that students tend to engage in exploratory investigation, and that emergent results from exploration often fuel more careful investigation. By leveraging these two affordances of design, inquiry through design supports a transition from what Schauble terms an engineering model of experimentation to a scientific model — a transition that may be more effective than simply scaffolding scientific investigation from the start (Schauble et al., 1991b).

Another element of design projects that may inform and scaffold student inquiry in other settings is the importance of physical artifacts in the investigation process. In design settings, physical articles represent design ideas (Roth, 1996). These artifacts can be empirically tested to evaluate the strength of the idea. But the artifacts also serve to document changes in students’ thinking about design ideas. By the end of the project, students may have accumulated a number of physical designs that represent the evolution of their thinking over the course of the project. These artifacts may then be used to prompt reflection or to represent design ideas to other students in the class.

Other inquiry-based projects also benefit from the use of artifacts to represent student thinking (Wisnudel, Stratford, Krajcik, & Soloway, 1996). The strength of this approach lies in the self-documenting nature of the artifact. If the students must build an artifact to represent an idea, whether it is a design prototype or a schematic of a laboratory investigation, the artifact serves to represent a specific set of ideas, predictions, and outcomes. These artifacts persist as students engage in multiple investigations and may be used to help the students to reflect on and make sense of the investigations as a whole.

Finally, the challenges that students face as they pursue inquiry are not unique to design contexts. Students face difficulties asking questions, planning investigations, and reasoning with evidence in any inquiry-based project environment. My work provides insight into the nature of specific scaffolding that may help students to engage in successful inquiry, including support for planning comparative investigations and support for evaluating empirical evidence and integrating past results with ongoing investigations.
7.3.3 Teaching Inquiry Through Design

Teachers play an important role in supporting student inquiry in the classroom (Crawford et al., 1999). I have described how teachers supported student inquiry through their framing of the design task as well as their interactions with students during the design project. An important research goal is to explore ways to frame and conduct classroom-based research that can inform teaching practice as well as contribute to broader theories of teaching and learning (Hammer, 1999).

This aspect of my research, intended to document teaching strategies for supporting inquiry through design, presumes that teachers approach their practice as reflective practitioners (Schön, 1987). The approach I have taken uses the thick description of narrative cases to provide context for teachers’ actions. I have presented teaching strategies as practices that address a particular set of goals and tradeoffs. This approach recognizes that teachers must satisfy a variety of classroom goals at once, and that these tradeoffs may place goals at odds with one another or require a teacher to defer a particular goal in order to address another (Hammer, 1997). For example, we have seen Lillian and Rachel take very different approaches to supporting student work during the design project, but similar approaches to assessing student work in terms of explanation. These differences and similarities reflect unique solutions that each teacher used to meet a different set of classroom goals.

Whereas individual strategies, presented in context, allow teachers to consider a range of potential options for practice, sets of related strategies together embody distinct roles for each teacher that can serve as generative metaphors for practice. Understanding these roles and the nature of practice associated with each role provides a more general framework within which teachers can customize instruction to meet specific classroom needs.

Together, these approaches — documenting specific strategies and identifying generative roles that inform multiple aspects of teaching practice — provide two levels of interpretation for how teachers support inquiry through design. Both seek to remain fine-grained enough to allow teachers to integrate these strategies into their own practice while also being explicit enough to remind teachers of the core issues the strategies were intended to address. Future work will explore the success of these approaches in contributing to the teaching of inquiry through design.
7.4 Implications for the Redesign of Inquiry Through Design

I described in chapter 2 how ITD was itself a product of iterative refinement, drawing on successful curricular design sessions and classroom field tests. In chapters 5 and 6, we saw that elements of ITD successfully support, to varying degrees, student inquiry in practice. This research informs another iterative redesign of this approach, offering several implications for how ITD might become more effective for supporting student inquiry.

Inquiry through design was originally intended to leverage design’s affordances for inquiry while minimizing any design goals that conflicted with student inquiry. The designers of inquiry through design curricula, including myself, chose to adopt tasks that reflected engineering design problems, without modifying or “watering down” these tasks to make them more suitable for inquiry. We believed that students would be able to pursue both performance and explanatory goals over the course of the project.

My research suggests that the next iteration of inquiry through design should reconsider this decision. We have seen how students often pursue goals of improving design performance, even when they know that their grade will not reflect this. In part, students’ attitudes reflect a view that “design trumps all”: performance, rather than explanation, becomes the ultimate arbiter of success.

These results imply that inquiry through design may be more successful if it abandons the goal of allowing students to pursue completely open-ended design. Instead, scaffolds that encourage students to pursue more comparative investigations should be explicitly incorporated into the design project.

Inquiry through design is comprised of four major elements: staging activities, an authentic design challenge, a structured design cycle modeled after a scientific investigation, and opportunities for iterative redesign. In the remainder of this section, I will explain how these elements of ITD might be recast to continue to support student design while providing greater support for more structured investigations.

7.4.1 Recasting Staging Activities

Staging activities were intended to provide data and principles that inform student reasoning during design. When students were able to use staging activity results, their
designs generally improved. However, students often did not draw on these findings. Even when students had recorded data and conclusions from these activities in their own lab notebooks, they did not refer back to these findings as they worked on their design project. This suggests that students had not integrated their understanding well enough to apply it in a design context.

Two new scaffolds may help students to relate these early activities to the design project. First, the principles and evidence gleaned from staging activities need to be made more accessible to students later in the project. Doug demonstrated one way to do this when he posted earlier results in the back of the room. Another approach might be to actively involve students in the construction of design resources by explicitly repackaging the earlier findings as a resource for later design. This approach, which engages students in the construction of “smart tools” or “rules of thumb” that can help them to solve later problems, has been shown to be effective in other project-based settings (Kolodner et al., 1998; Vye et al., 1998).

Second, students should be prompted during the design process to reflect on these results and propose ways in which they could inform their work. This can be achieved in different ways. Learning By Design addresses this issue by weaving benchmark activities throughout the design challenge. In this model, activities are only presented once their utility has been established by the design context (Hmelo et al., 2000). However, such an approach relies primarily on the activities, rather than the design cycle, to support student investigation; design is used more as a motivating context for a series of predefined investigations.

Inquiry through design may benefit from this work by introducing the design project earlier in the overall curriculum. Currently, reflective questions in the staging activities ask students to think about how what they have learned may be applied in a general design context. These questions could be refined to focus students on the specific design project that they will pursue.

Another approach may be to use reflective prompts to encourage students to revisit earlier evidence in light of the current design challenge. The Knowledge Integration Environment has reported some success using reflective prompts to encourage students to explain how evidence relates to an ongoing investigation. In these settings, students were better able to integrate their knowledge, applying their understanding to new problems and new settings
Inquiry through design may draw on this work by inserting into the design project reflective questions that specifically prompt students to refer back to earlier activities and to think about how these activities might inform their design decisions. Combined with the construction of design resources and more pointed reflection during the staging activities, these refinements may improve students’ ability to reason about how evidence and principles from the staging activities informs design.

7.4.2 Refining Criteria for Effective Design Challenges

A current issue in the literature is the question of what constitutes an effective, appropriate, or authentic design challenge. Several researchers who have constructed design-based curricula have sought to define criteria for good design challenges (Hmelo et al., 2000; Sadler et al., 2000).

We have seen that the nature of the design challenge plays an important role in shaping the nature of student inquiry. For example, the design challenges used in inquiry through design need to consider the nature of explanations that students will be able to construct from empirical evidence. Not all domains afford deep causal explanations, and we have seen that materials science is often problematic in that way. Effective design projects will be those that allow students to infer causal explanations from the designs themselves.

The set of refinements for design challenges that I present here provide a framework for reviewing, and challenging, recent criteria for effective design challenges. Current suggestions for creating effective design challenges assume that design is used as a means to drive student inquiry (Hmelo et al., 2000; Sadler et al., 2000). This goal is consistent with inquiry through design, and suggests that the refinements I describe may inform ongoing conversations within the field on the nature of effective design challenges.

Choose domains that support student inference of visible phenomena. One principle that underlies the use of design is the premise that students will be able to infer scientific principles from the process of building and testing physical designs. Researchers differ on the degree to which this will occur. Sadler argues for design challenges that allow students to infer causal principles with little external guidance (Sadler et al., 2000). Hmelo and Kolodner provide significant scaffolding and related activities to help students to make these connections.
(Hmelo et al., 2000; Kolodner et al., 1998). However, in all cases, students are expected to be able to observe phenomena and infer causality from the design itself.

This approach is compromised if design challenges involve materials in which causality is invisible or time-delayed. Hmelo describes the challenge of helping students to infer the relationship between the circulatory and respiratory systems by building model lungs (Hmelo et al., 2000). Unfortunately, the mechanisms by which gas exchange occurs are not visible to the students. Many design challenges based in materials science face similar problems. Explanations for why different materials have different physical properties often require an understanding of the molecular properties of the material, an understanding that students will not achieve through design alone. (However, it is worth mentioning here that materials scientists do not completely understand the chemical process by which cement reacts with water to form concrete (Biernacki & Walhof, 1998, p. A10). Students who investigate a range of concrete formulations may very well be participating in authentic materials science research!)

This suggests that effective design challenges should focus on developing an understanding of physical or mechanical properties that can be observed by students. Penner’s work using design to explore the mechanical function of the elbow is a good example of this criteria (Penner et al., 1998). While it does not rule out using design to explore other domains, this criteria does suggest that careful attention be paid to provide scaffolds to help students to infer invisible or time-delayed behavior, perhaps through staging activities, simulations, or other means that can render invisible behavior visible.

*Seed challenges with controversial ideas.* Design challenges may also be refined to encourage students to argue about controversial or competing ideas. This approach draws on the finding that students generate personally relevant design questions more often around surprising or controversial ideas. This finding is consistent with research from the Knowledge Integration Environment that suggests that structuring student design around ambiguous or controversial statements provides an initial question that drives later student research (Cuthbert & Hoadley, 1998; Linn & Hsi, 2000). Identifying a small number of catalyzing design ideas, and presenting these ideas as possible design directions, may help students to adopt their own questions sooner in the design process.
Sadler also seeds design challenges, but instead of using a controversial idea, his approach provides students with an initial prototype design that serves as benchmark for design improvement (Sadler et al., 2000). Rather than suggesting a range of design possibilities, this guarantees that all students begin the design process at the same point. This scaffolds student design by providing students with an initial working prototype that they can modify to try to improve performance. Although this approach is intended to reduce situations in which students have trouble meeting minimal performance standards, it may bias students to explore design ideas within a limited range; few students may completely abandon the prototype design to try something radically new.

A compromise might be to provide a set of working design prototypes that all perform equally well. Students could be encouraged to pursue those designs that they believe offer the most promise for improvement. This would address the need to introduce competitive design ideas into the project and the need to scaffold successful design by providing a baseline prototype.

Support rapid iteration. We have seen that providing opportunity for iterative redesign provides students with more opportunities to plan investigations to pursue their own questions, and that these questions often emerge from design testing. Design challenges that afford rapid design iteration may be more productive because they will support a greater number of design iterations in a fixed amount of time.

For example, design cycles in the Concrete Module lasted at least four days, as students had to wait for the concrete to cure. In contrast, students in the Composites module were able to iterate on design ideas several times over one period. Although projects may still be structured around topics like concrete, support for more complex investigative strategies may need to be provided to help students plan investigations that let them explore multiple design ideas and generate evidence to distinguish among those design ideas. Further, simulation environments may complement such design contexts by supporting rapid iteration to help students explore a range of design ideas before they begin to design with physical materials.
7.4.3 Supporting Design Investigation

My findings have shown that students can engage in successful design investigations. However, elements of student inquiry, particularly the planning of comparative investigations, could be better supported to make student investigation more productive. Recent research on supporting student investigation in learning environments can inform the refinement of the design cycle to better scaffold student inquiry.

In addition to improvements to the written materials, it should be clear from my research that the teacher plays an important role in scaffolding investigation. My results encourage teachers to adopt roles in the classroom that allow them to provide proactive scaffolding for student investigation, much as Lillian did. The refinements proposed here are intended to complement teacher scaffolding of student inquiry.

One potential scaffold would be a structured tool for supporting multiple investigations. Such a tool would help students document the results of design tests, and help them construct productive comparisons across tests based on the design elements present in each design variant. Learning By Design uses a similar technique involving “design pin-ups,” where students post versions of their design for comparison and critique among other students (Kolodner et al., 1998).

In a similar vein, Sadler uses design storyboards that chronicle changes in design over the course of the project to document multiple design ideas (Sadler et al., 2000). However, these storyboards are constructed post hoc, largely because students continually modify their design over the course of the project. This means that earlier design variants are not preserved; changes are made to the design artifact itself. This approach exacerbates the importance of tracking design investigations because it makes it harder for students to reconstruct their work; earlier versions have been incorporated into later ones.

An appropriate compromise of these approaches might be a structured design journal that prompts students to document designs as they are built and to identify the unique features and design elements of each variant as they iterate. Focusing student attention on the changes between each design iteration is an important strategy for helping students to engage in comparative investigation. Journal entries should be made during the design project so that students can capture changes to their designs as they happen. Students could
include pictures of their designs to help document each design iteration, a particularly important step if students are continually refining a single design over time. Students can then compare journal entries to see the important differences among various designs.

A computer-based tool might even be able to suggest or highlight particularly productive comparisons given students’ current results and predictions about design performance. For example, the Progress Portfolio could provide a means for students to capture digital photos or even video of their designs, annotate their designs with rationale for particular features, and document design performance (Loh et al., 1998). However, adding computer-based technology to what is a fairly low-resource project may prove difficult in some school settings.

Another potential scaffold for supporting student investigation is the introduction of a formal exploration phase to the project. This scaffold builds on Schauble’s argument to transition students from an exploratory model of investigation to a comparative model (Schauble et al., 1991b). In its current form, inquiry through design prompts students to consider a range of design ideas during an initial brainstorming phase. The intent of this activity is consistent with what I am proposing, but the implementation is not: during brainstorming, students typically do not have access to design materials, nor can they engage in exploratory testing. Thus, they have no way of empirical testing their design ideas.

Learning By Design incorporates an explicit exploratory design phase that some researchers refer to as “messing about” (Hmelo et al., 2000; Kolodner et al., 1998). This phase allows students to explore a variety of design ideas. Students are not required to document their actions or generate evidence to support certain design ideas. Instead, students explore different approaches to identify promising design ideas that can be investigated more closely at a later stage. This approach is also consistent with the use of screening heuristics in scientific investigations (Beveridge, 1950). Here, screening is used to narrow the space of possible investigations before engaging in more comparative scientific inquiry.

Adding a formal exploratory phase to inquiry through design would allow students to engage deeply with the materials at hand and to begin to identify promising ideas. Following the exploratory phase, students could share with the class their design ideas and any supporting evidence for these ideas. The controversies and surprises that result from
this phase then become fodder for an investigation phase, in which students choose a small number of promising design ideas and plan investigations to prove which ideas work the best. To help students to retain an explanatory goal, it will be important for teachers to engage the class in a discussion to explain the epistemological shift from one phase to the next.

7.4.4 Retaining Redesign

We have seen that student questions and investigations tend to improve over the course of design iterations, a practice consistent with others’ findings (Sadler et al., 2000; Scardamalia & Bereiter, 1992; Schauble et al., 1991b). This finding is also consistent with research in project-based science that suggests that providing time for students to engage in deep investigation of scientific phenomena is one of the most important elements of successful classroom practice (Beeth & Hewson, 1999; Crawford et al., 1999).

These findings suggest that iterative design is an important part of the project, but one whose advantages need to be better communicated to teachers. Studies such as this one, which provide detailed narratives of student engagement in inquiry, may help teachers new to design to see the benefits of redesign and commit classroom time to encourage it.

Further, it is important to consider the nature of design iteration. We have seen that students in Rachel’s class who engaged in linear iteration — progressively modifying a single design over time — had trouble identifying specific design ideas that contributed to design performance. In this case, providing time for iterative design may be seen as counter-productive because students use the time to further exploration. Opportunities for redesign will be most effective when the design investigation process is scaffolded to help students generate comparative evidence that will inform later design iteration.

Of course, additional iteration implies more data for students to organize and analyze. The refinements that I have suggested for supporting design investigation may also contribute here by helping students to organize the results of multiple design trials and keep track of which design ideas have been tested, and in what combinations.
7.4.5 Summary

The changes described here draw on my research as well as recent research in science education to inform the refinement of the inquiry through design approach. I contend that these refinements may improve the use of engineering design contexts to support student inquiry. An important theme of these suggestions is that idea that student design must be carefully structured. Completely open-ended design, while motivating, encourages the adoption of design performance goals at the expense of developing an understanding of why designs work. The refinements proposed here add structure to the design task in order to help students to move from design exploration to scientific investigation.

7.5 Inquiry and Design, Research and Practice: Implications for Future Work

My work is situated within a research community that itself balances design and inquiry. The field of learning sciences conducts research on learning from cognitive and sociocultural perspectives and applies research on learning to design and study effective learning environments in a variety of settings.

Over the past decade, the field has gradually moved away from lab-based research and towards more and more realistic learning settings. In the early 1990’s, Ann Brown’s pioneering call to pursue design experiment research into classrooms (Brown, 1992), coupled with arguments for attending to the role of social context in learning (Brown & Campione, 1990; Brown et al., 1989; Lave & Wenger, 1991), helped the field leave the psychology lab to take on learning in authentic, messy classroom environments. In the ensuing decade, many researchers adopted a design experiment approach, which further blurred the distinction between research and practice in the learning sciences.

7.5.1 Moving From Theory to Practice

In the last few years, we have seen yet another shift. Although many researchers are now engaging in design experiment research, claims that these classrooms represent truly “authentic” learning environments have begun to ring false. Researchers are acknowledging that learning outcomes documented in resource-rich classrooms with direct access to university researchers and graduate students may not translate to everyday practice (Krajcik et al., 1998). In response, new efforts are reaching out and exploring new questions about
how innovative learning environments fare when placed in the hands of many teachers in distant districts.

My work speaks to this transition. At one level, it meets the challenge of moving from theory to practice by providing a description of an innovative approach to science inquiry that is used in different realistic classroom contexts. It describes how each teacher adapts the approach to meet specific classroom needs and discusses how core aspects of the innovation contribute to student inquiry within these classrooms. By demonstrating that students can engage in inquiry in multiple classroom settings, it argues for design as a viable context for scientific inquiry.

At another level, my work offers a methodology for documenting and assessing the impact of innovative science curricula in realistic classroom settings. The narrative cases provide rich detail of classroom practice and document the tradeoff teachers face as they struggle to align the goals of the written curriculum with their own classroom goals and the needs of their students. This approach is particularly germane to project-based work because it is designed to follow students over the course of the project. The strength of the approach is that it provides a coherent narrative of student decision-making, enabling researchers and educators to examine how decisions made earlier in the project affect student engagement in inquiry at later stages. The characterizations of student inquiry that result may help science educators to understand the particular struggles students face and the ways in which scaffolding can support the inquiry process.

7.5.2 Future Directions

My research naturally extends in two directions: toward stronger uses of design contexts in science, and toward a better understanding of the nature of teacher practice and teacher adoption of innovation.

I have shown that inquiry through design can be an effective means of engaging students in scientific inquiry. I have also suggested a number of refinements to inquiry through design that are based on my own empirical research as well as findings reported by others engaged in similar research.

An important continuation of the work will be to explore the use of inquiry through design to create new design projects. Design projects in new subject domains will test the
robustness of the ITD approach, particularly in the selection and refinement of effective
design challenges. Such research will inform further iteration of the instructional approach
and the scaffolds that support student learning in design contexts. New classroom settings
will help to refine the flexibly adaptive nature of ITD by exploring how other teachers
reconcile their own teaching practice with the goals and support provided by inquiry
through design.

Teachers, as reflective practitioners, are designers of their own practice (Schön, 1987). They
continually refine their practice and their curriculum to meet the particular constraints of
their own classroom context. Viewing teaching as a designed activity lends itself well to
characterizing teachers’ strategic decisions. These decisions take into account the unique
goals and constraints of a teacher’s classroom context. Similarly, the strategies teachers use
to support student engagement in inquiry also reflect a particular set of tradeoffs, such as
Rachel’s willingness to let students struggle as they learned to be more independent in her
classroom.

More and more, professional development efforts are encouraging teachers to participate in
ongoing conversations about practice. Communication technologies are being used to create
communities that share, rather than dictate, ideas about teaching and learning (Hsi, 1999;
Schlager & Schank, 1997). It is easier than ever for teachers to share their experiences with
designers and researchers. Within this context, we need to understand how teachers adopt
innovation, and how researchers and developers can provide support to help teachers
integrate innovative ideas into their practice in ways that meet everyone’s goals for science
education and student learning. Several projects have begun to partner with schools and
teachers to explore these issues of adaptive design that retains core instructional innovations
while meeting local needs (Blumenfeld, Marx, Krajcik, Fishman, & Soloway, in press;
Schneider, Krajcik, & Marx, 2000; Schwartz, Lin, Brophy, & Bransford, 1999).

My work is one step in this direction. It provides a methodology to document strategies that
contribute to student inquiry, but qualifies these strategies in context, helping teachers who
view this work to understand the constraints under which these strategies were effective
and to consider how their own constraints relate to the classroom in question. Future work
will continue to build on this approach, respecting the teacher as a reflective practitioner
and refining methods to document teaching strategies.
Chapter 8. References


REFERENCES


Appendix A. Overview of the Composites Module

Through the activities, students will learn about the attributes and advantages of composite materials. Each activity prepares students for the design projects, in which they are challenged to build a fishing pole or to invent a new composite material of their own.

Staging Activities

Activity 1: Testing Different Kinds of Ice

By comparing pure ice with ice reinforced with bathroom tissue, students learn what composite materials are and discover their relative strengths. The goal is to show that two or more materials can be combined to form a material with improved properties over those of the starting materials. The activity is a dramatic introduction to composite materials, and builds enthusiasm for the following activities.

Activity 2: Hunting for Composite Materials

Students search their surroundings for objects made of composite materials. They discover that composite materials have a variety of uses that take advantage of specific properties of the composites. By thinking about the functions of the various objects they find, students come to understand that materials are designed for particular purposes or functions.

Activity 3: Exploring the Difference Between Strength and Stiffness

Students test a variety of materials qualitatively and rank their strength and stiffness, two important structural properties for materials that carry a load. Students learn that a strong material does not break easily nor does a stiff one deform much. The purpose is to help them evaluate a material’s strength and limitations and to consider how materials may be combined to complement one another when designing a composite.

Activity 4: Testing a Foam Composite for Strength and Stiffness

When a plain beam made out of polystyrene gets reinforced, top and bottom, with a strip of poster board, the resulting composite is much stronger and stiffer than the original beam.
Students learn about the importance of good bonding when constructing layered composite foam beams. The objective is to determine the strength and stiffness quantitatively by measuring maximum loads and deflection curves (cantilever test).

**Activity 5: Geometric Reinforcement (optional)**

Students wrap foam beams with fiber-reinforced tape to explore the importance of the geometric orientation in laminar reinforcement. By varying the design of reinforcement orientation, student will realize that the structural arrangement of reinforcing elements (e.g. the relationship between the direction of the fibers in the tape in the direction of force placed upon the beam) has a considerable effect on its mechanical properties.

**Research Project: Researching Composites (optional)**

With this independent research project, students go to the library to find information on modern composites, how they were developed, how they are manufactured, and what people use them for. They get a first-hand view of the close interconnections between science, technology, and society, and write a formal report.

**Design Projects**

**Design Project 1: Designing a Fishing Pole**

Based on what they learned about strength, stiffness, and composites testing and construction, students will build the strongest, most flexible, and lightest fishing pole. It should be stiff enough to provide, say, good sensitivity to slight jerking motions, yet be flexible enough for casting a line. First they design the prototype, then build and test it. Then they discuss and analyze their results within their group and suggest alterations to their design and/or testing protocol that might improve the strength/weight quotient of their pole. Students then construct and test their redesigned fishing pole. Finally, all groups will compare their designs and results and discuss the design process.

**Design Project 2: Designing a New Material**

Students will build on their independence as they design, test, evaluate and redesign a composite material of their own making for whatever use they deem appropriate. The
project simulates the process engineers use when they work on new designs and may inspire some students to look into a career in the applied sciences.
Appendix B. Overview of the Concrete:  
An Infrastructure Material Module

Through the activities, students learn about the attributes and advantages of concrete. Each activity prepares students for the design projects, in which they are challenged to make a concrete roofing tile or to invent a new concrete product.

Activities

Activity 1: Hunting for Objects Made of Concrete

By identifying concrete objects in their surroundings, students recognize the widespread use of concrete as an infrastructure material. From their observations, students attribute formability, strength, durability, and low cost as the reasons why concrete is the most common infrastructure materials used today.

Activity 2: Comparing Different Kinds of Cements

Students observe changes that occur as cement hardens and conclude that the cement-hardening process involves chemical and physical changes. Students also learn that additives can affect rate at which cement cures. The goal is to show that, when mixed with water, portland cement forms a pastelike material that hardens with time and is the critical component used to bind other materials in concrete.

Activity 3: Comparing Different Concrete Formulations

Students make concrete samples using different formulations. They discover that the density of concrete can be changed by changing the proportions of its components—coarse aggregate, fine aggregate, cement, and water.

Activity 4: Testing Properties of Concrete

Students examine why brittle materials fail and how the strength of materials like concrete is affected in states of tension and compression. Using the cement and concrete samples they
made in the previous Activity, students learn that the proportions of the components in concrete can affect its strength and brittleness. They realize that, when tested under tension, concrete can be extremely strong when the right balance of fine and coarse aggregates and the correct proportion of water and cement are used.

Activity 5: Reinforcing Concrete

Students test the effects of three types of reinforcing materials—metal bars, screens, and short fibers—on the strength and brittleness of concrete. They draw conclusions about the way that each type of reinforcement improves the properties of concrete. The purpose is to show how reinforcements in a concrete mix can make it stronger in tension and less susceptible to fracture.

Design Projects

Design Project 1: Designing a Concrete Roofing Tile

The concrete roofing tile design project can be used as a closing activity for the unit on concrete materials. This project allows students to demonstrate what they have learned about concrete materials in the activities. Students will design a concrete roofing tile that must meet specific design and performance criteria. The tiles must be strong, lightweight, and must not fail completely upon impact. Students make the prototype roofing tile which they have designed, and subject the tiles to impact and other tests, according to the design specifications. They discuss and analyze their results within their group and suggest alterations to their design and/or testing protocol which might improve the their concrete tile. Students then construct and test their redesigned tile. Finally, all groups compare their designs and results and discuss the design process.

Design Project 2: Designing a New Concrete Product

Possible uses of concrete are explored in this Design Project. Students design and test prototypes of a new concrete product of their choice and, based on their data, draw conclusions about the feasibility of their proposed product.
Appendix C. Interview Protocols

Student Interview Protocol

Target interview length: 15-20 minutes. Interviews were taped, dubbed to digital format, and transcribed.

A. Explaining Their Design

Note: Talk me through their first set of designs, why they work. Do they give evidence? Did they make tradeoffs? Push them to justify their claims.

• What were the goals for this unit? For the design project?
• Tell me about your set of designs. What did you make? What does it have to do? Why did you use the materials you did? What else did you consider? What did you vary? Did the other activities you did help you in your design? How? [Mold; mix; reinforcement.]
• Where did these ideas come from -- other activities, background knowledge...
• What criteria did you use to evaluate the design?
• Prediction: Which designs did you think would work? How could you tell?
• Results and analysis: What happened when you tested them? What did you learn from these designs? From other designs in the class?

B. Redesign and Further Investigation.

• Do you think the criteria you used to evaluate the fishing poles made sense? Are there other things that should have been factored in?
• Can you think of any information that would help you improve your design? How could you get that information? [Experiment, research, etc.]
• If you redesigned your object, what would you do differently? [Why? Evidence?]
C. Perceived Goals and Learning

Note: I want to start open-ended and focus on their perceived goals and learning outcomes.

- What did you learn by doing this unit? How did you learn that? [Process and content, authenticity. Dig to get source of learning.] Is there anything (else) you feel you could do better now than when you started this project?
- What was hard about this project? Why was that hard? [New: Get at where they felt they needed to spend their time.]
- How important was performance in this project? [For you, for the teacher, for the grade.]
- How important was being able to explain why your design worked? [For you, for the teacher, for the grade.]

D. Views of Science and Design

- How typical is this kind of project for a science class? Why is it the same or different as other things you do in science? [Is there some other class that fits these projects better than science?]

Teacher Interview Protocol

Target interview length: 30-45 minutes. Interviews were taped, dubbed to digital format, and transcribed.

A. Open-ended

Note: Let them give me their initial sense for how things went?

- So, how did you feel the project went?

B. Goals

Note: Make sure this covers performance and explanatory goals. For each, focus on typicality, how it’s communicated and assessed, and how challenging it is for the students.
• What did you want students to get out of the project? [Define; use examples.]
• Are these goals fairly typical for your classroom?
• How did you communicate those goals to the students? [Assessment, telling them, the materials do it for me, etc.]
• Did they reach those goals?

C. Assessment
• How were students assessed?
• How important was performance? Explanation? Do you think the assessment reflected that?

D. Module Structure
• What was the relationship between the activities and the design project?
• Why iterate? [Is iteration a good thing?]
• What do you feel was your role in this project?

E. Inquiry and Design
• Do you feel that inquiry was going on during this unit? [What do you mean by inquiry? What’s important about it? How can you tell it’s happening?]
• How do you help your students to do inquiry? [Framing of task; management of student work.]

F. Comparisons
• Was this unit different for your students? How?
• Was this unit different for you? How?

G. Curriculum Redesign
• What would you do differently? [Best answered about each individual question, not the whole.]
# Appendix D. Design Process Element Tables

## TABLE D.1.
**DESIGN DECISIONS FROM LILLIAN’S GROUP (KATHY, SARAH, AND JOHN).**

<table>
<thead>
<tr>
<th>Design Proposal</th>
<th>Design Question</th>
<th>Design Investigation</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day 1 (Design brainstorming)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kathy proposes using pipe cleaners.</td>
<td>How will pipe cleaners contribute to the design’s strength and stiffness? (P)</td>
<td>Planned five design variants, each of which used a different number of pipe cleaners. (C)</td>
<td>Not tested. Design idea initially accepted; proposal abandoned once telephone wire proposal was made.</td>
</tr>
<tr>
<td>Teacher suggests using tape; group quickly names several kinds of tape.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Teacher reminds group of importance of bonding composite materials together; Kathy proposes using glue.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Day 2 (Planning and building first set of design prototypes)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sarah proposes using telephone wire.</td>
<td>How does telephone wire contribute to the design’s strength and stiffness? (P)</td>
<td>Planned five design variants, each of which varied the amount of telephone wire. (C)</td>
<td>Tested. Results surprised the group and led to their redesign investigation.</td>
</tr>
<tr>
<td>Students propose slicing open the straws to make it easier to fit the wire inside them.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Day 3 (Testing)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Day 4 (Interpreting and presenting results)</strong></td>
<td></td>
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<tr>
<td><strong>Day 5 (Redesign of a set of design prototypes)</strong></td>
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<tr>
<td>Students propose dissecting the telephone wire and using only the smaller wires inside the plastic sheath.</td>
<td>What parts of the telephone wire, the inside wires or the outside sheathing, contribute to strength and stiffness? (P)</td>
<td>Planned five design variants that varied the number of smaller inside wires to larger sheathing. (C)</td>
<td>Tested. Results surprised the group.</td>
</tr>
<tr>
<td>Teacher proposes that students explore materials that reinforce the outside of the straw.</td>
<td>Proposal rejected; students are focused on their own investigation of the wire.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE D.2.
DESIGN DECISIONS FROM RACHEL’S GROUP (LISA, ELLEN AND CARRIE).

<table>
<thead>
<tr>
<th>Design Proposal</th>
<th>Design Question</th>
<th>Design Investigation</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellen proposes using a</td>
<td>How will modeling clay contribute to design performance? (S)</td>
<td></td>
<td>Students incorporate the idea into their design after a short discussion to clarify the value of the idea (flexibility).</td>
</tr>
<tr>
<td>plastic rod to reinforce the</td>
<td></td>
<td></td>
<td>Adopted after Ellen relates the fibers in duct tape to an earlier activity on directional reinforcement.</td>
</tr>
<tr>
<td>inside.</td>
<td></td>
<td></td>
<td>The proposal is controversial; the students disagree about what clay would do. The proposal is tabled for the moment, but will return the next day.</td>
</tr>
<tr>
<td>Ellen proposes using</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>duct tape to reinforce the</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>outside.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carrie proposes using</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pipe cleaners to reinforce</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>the inside.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group proposes using wood to</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>reinforce the inside.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ellen proposes that they</td>
<td>What material will best reinforce the inside of the design: the plastic rod,</td>
<td>Led to the sequential investigation of several different</td>
<td></td>
</tr>
<tr>
<td>focus on reinforcing the</td>
<td>modeling clay, or wood? (P)</td>
<td>materials. (E)</td>
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</tr>
<tr>
<td>inside of the straw, and that</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>they will learn from other</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>groups how to reinforce the</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>outside of the straw.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What materials will best</td>
<td></td>
<td>Students planned to let other groups investigate this</td>
<td></td>
</tr>
<tr>
<td>reinforce the outside of the</td>
<td></td>
<td>question. (N)</td>
<td>No followup.</td>
</tr>
<tr>
<td>design? (S)</td>
<td></td>
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</tr>
</tbody>
</table>

Day 1 (Design brainstorming)
<table>
<thead>
<tr>
<th>Day 2 (Building and testing first set of design prototypes)</th>
<th>Lisa proposes using metal wires, a material she found at a local craft store.</th>
<th>What other materials (in the craft store) are suitable for the design project? (S)</th>
<th>Lisa hand-tested several materials at the store for flexibility before settling on the wires. (E)</th>
<th>Based on Lisa’s tests, students incorporated metal wires into a design with the plastic rod. (PROTOTYPE 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group proposes a first design prototype that uses the metal wires and plastic rod for reinforcement.</td>
<td>How well will this design perform? (P)</td>
<td>Group formally tests their first prototype for strength, flexibility and mass. (E)</td>
<td>Design fails to meet the flexibility criteria; it does not “bounce back” to its original shape once the weight is removed.</td>
<td></td>
</tr>
<tr>
<td>During testing of their first design, the group argues over how to interpret their test results.</td>
<td>How far does a design have to “bounce back” to pass the flexibility criteria?</td>
<td>Students test their design twice to see if the test is consistent, and then ask the teacher.</td>
<td>Teacher reiterates testing criteria, confirming that the design failed when tested. Students focus efforts on finding a material that can “come back” to its original shape</td>
<td></td>
</tr>
<tr>
<td>Students search for a material that can keep its shape after it is bent.</td>
<td>What materials have the property of keeping their shape? (S)</td>
<td>Students begin search the classroom for materials that meet this criteria, testing materials they find by hand. (E)</td>
<td>Search leads to several new design ideas described below, included wet wood and fiber optic cables.</td>
<td></td>
</tr>
<tr>
<td>Ellen again proposes using modeling clay to reinforce the inside and help the straw keep its shape.</td>
<td>Will modeling clay help the straw keep its shape? (P)</td>
<td>After much debate, Lisa agrees to help Ellen construct a design with clay in order to be able to test the idea and, in Ellen’s words, “prove me wrong.” (C)</td>
<td>The comparative experiment is abandoned when the group hits a logistical snag: they can’t figure out how to get the clay inside the straw.</td>
<td></td>
</tr>
</tbody>
</table>
Another student claims that wet wood works well.

Carrie examines the list of what works and what doesn’t that students have been updating on the board. She reports back that wire, wrap, and wet bamboo do not work.

Lisa adopts the idea and begins incorporating it into a design.

Lisa abandons the wet wood design idea based on Carrie’s report.

Lisa and Carrie propose their second design prototype, adding a length of fiber optic cable, removing some of the metal wires, and leaving the plastic rod in place.

Will adding fiber optic cable (and removing some wires) improve the design? (P)

Students build and test the prototype, which varies from the first prototype in two ways (addition of fiber optic; removal of wires). (E)

Students find the same results; the design fails to return to its original shape.

When asked by the group, Rachel suggests using wood skewers.

Students adopt her idea.

Students propose a third design prototype which adds wood skewers and removes the remaining metal wires.

Will adding wood skewers (and removing wire) improve the design? (P)

Students build and test the prototype, which splinters when tested. (E)

The design splinters and fails when tested.

Weekend investigation

Group proposes an experiment to disentangle the effects of their earlier prototypes.

Which material – wood skewers, fiber optic cables, or wires -- best reinforces the inside of the design? (P)

Students build and test three variants to compare the effects of the wood skewer, the fiber optic cable and the wires. (C)

The empirical results suggested that the wires were not an effective means of reinforcement, but that both the fiber optic cable and the wood designs performed well.
Day 3 (Redesign of a single prototype)

<table>
<thead>
<tr>
<th>Group proposes combining fiber optic cables and wood into a single design</th>
<th>Design proposal was adopted. Decision was based on results from weekend investigation that showed that these two materials performed well.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group proposes replacing duct tape with strapping tape</td>
<td>Design idea was adopted. Although students had not done tests to compare these materials, they argued that strapping tape is lighter and “more reinforced”.</td>
</tr>
<tr>
<td>Another student reports that “fiber optic doesn’t work.”</td>
<td>Based on this claim, the group abandoned the fiber optic component of their design and focused exclusively on wood.</td>
</tr>
<tr>
<td>Do fiber optic cables reinforce the design? (P)</td>
<td>The student argued that the cable was too heavy and didn’t bounce back, but didn’t provide any specific data. (N)</td>
</tr>
<tr>
<td>What made the wood skewers successful over the weekend, its material or its shape? (P)</td>
<td>Ellen argued successfully that the shape of the wood was more important because a design with shorter pieces would fail at the juncture. (N)</td>
</tr>
<tr>
<td>Faced with a material shortage, the group proposes building their original redesign idea, using fiber optic cables and a wood skewer formed by overlapping two shorter pieces of wood.</td>
<td>Students built one design and tested it. (E)</td>
</tr>
<tr>
<td>Will combining fiber optic cables and wood result in a better design? (P)</td>
<td>Design improved on earlier designs by this group.</td>
</tr>
<tr>
<td>Design proposal</td>
<td>Design question</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------------</td>
<td>------------------------------------------------------</td>
</tr>
<tr>
<td>Students proposed drawing on staging activity results, which explored the ratio</td>
<td>How does the ratio of coarse to fine aggregate affect</td>
</tr>
<tr>
<td>of aggregate to strength, to see if these results also held for heat conductivity.</td>
<td>heat conduction? (P)</td>
</tr>
<tr>
<td>Students proposed using only water and cement “just to see different mixtures.”</td>
<td>What would happen if we used only water and cement?</td>
</tr>
<tr>
<td></td>
<td>(E)</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>

TABLE D.3.
GROUPS FROM DOUG’S CLASSROOM (BETH AND LUKE; LOIS AND LARRY).
<table>
<thead>
<tr>
<th>Students proposed using the two strongest designs from the staging activities, since their design also valued strength. Larry proposed investigating whether the use of paper clips to reinforce one of the two designs really mattered.</th>
<th>What makes the designs effective, reinforcing paper clips or the mix ratio itself? (P)</th>
<th>Students built two designs, one that included paper clips (a) and one that didn’t (b). (C)</th>
<th>Results showed a slight performance gain of (a) over (b). Students noted that when (a) broke, “the paper clips held it together.” However, both of these designs were substantially outperformed by (d) and (e).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students wondered what would happen if they put a lot of sand in one design.</td>
<td>What would happen if there was a lot of sand in it? (S)</td>
<td>Students built one design (c) that was mostly sand. (E)</td>
<td>Design fell apart when it was removed from its mold.</td>
</tr>
<tr>
<td>Students wondered what would happen if they only used water and cement.</td>
<td>What if we only use water and cement? (S)</td>
<td>Students build one design (d) with no sand. (E)</td>
<td>Along with (e), this design yielded the best trial results.</td>
</tr>
<tr>
<td>Students proposed adding additional cement to their initial design to see what would happen.</td>
<td>Would adding more cement increase the strength of the first design? (P)</td>
<td>Although a different experiment from their first, the group built a design (e) that varied from (b) by increasing the amount of cement. (C)</td>
<td>This design proved the best of the five. Students speculated about why it outperformed (d), but the two designs varied in both amount of cement and amount of sand used.</td>
</tr>
</tbody>
</table>

| Lois and Larry (bowling balls) | Students built two designs, one that included paper clips (a) and one that didn’t (b). (C) | Results showed a slight performance gain of (a) over (b). Students noted that when (a) broke, “the paper clips held it together.” However, both of these designs were substantially outperformed by (d) and (e). |
|---|---|---|---|
| Students built one design (c) that was mostly sand. (E) | Students build one design (d) with no sand. (E) | Along with (e), this design yielded the best trial results. | This design proved the best of the five. Students speculated about why it outperformed (d), but the two designs varied in both amount of cement and amount of sand used. |
Scientific inquiry involves students progressively developing key scientific ideas through learning how to investigate. In this way, students build their knowledge and understanding of the world around them through the process of inquiry. Although sometimes described as discovery based learning, this doesn’t need to be the case. The article below by Kirschner et al. (2006) is a good summary of the potential problems associated with an unguided, inquiry approach (this critique is responded to by Hmelo-Silver et al. (2007)). That said, that are some strong, motivational reasons why you might like Doing Science: The Process of Scientific Inquiry. under a contract from the National Institutes of Health National Institute of General Medical Sciences. Center for Curriculum Development 5415 Mark Dabling Boulevard Colorado Springs, CO 80918. Teaching Standards The suggested teaching strategies in all of the lessons support you as you work to meet the teaching standards outlined in the National Science Education Standards. This module helps teachers of science plan an inquiry-based science program by providing short-term objectives for students. Scientists design and carry out investigations. Scientists think logically to make relationships between evidence and explanations. The TSM for sciences contains support for developing the written, taught and assessed curriculum. It provides examples of good practice, including course overviews, assessment tasks and markschemes, as well as student work with teacher comments. The main approach to teaching and learning sciences is through structured inquiry in the context of interdisciplinary units. Students are encouraged to investigate science by formulating their own questions and finding answers to those questions, including through research and experimentation. To enable students to design scientific investigations independently, teachers must provide an open-ended problem to investigate.