MERGING ENGINEERING AND SCIENTIFIC REASONING: HIGH SCHOOL STUDENTS' USE OF EVIDENCE DURING DESIGN PROJECTS

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Abstract

Design has the potential to be an effective context for scientific inquiry because it offers both motivation and opportunity. However, students engaged in design often focus on optimizing design performance rather than constructing scientific explanations for that performance. Further, students need support to effectively generate questions to explore, design experiments to test their theories, and use evidence to support scientific explanations.

How might we structure design contexts to support student inquiry? In this paper, we describe a model for supporting scientific inquiry situated within an engineering design context. The model, termed inquiry through design, structures the design context to provide opportunities for inquiry, while also providing curricular support for the inquiry process. This model is the basis for the creation of several curricular modules intended for use in high school science classrooms.

We report on one aspect of student engagement in inquiry, the role of evidence in student explanations. We describe how student generation and use of evidence to support explanations is influenced by the particular context for the explanation, such as arguing with another student over who has the better design, or making a formal class presentation about a design. In addition, we analyze the effect of written and enacted scaffolds on student use of evidence, specifically how such scaffolding may help students produce evidence that can be used to support explanations.

Introduction

Situating inquiry within design contexts

A major thrust of recent science reform efforts has been to engage students directly in scientific inquiry, which is thought to be a more authentic and effective learning context for scientific principles (Linn, diSessa, Pea, & Songer, 1994; NRC, 1996). This sense-making approach to science allows students to design investigations, gather evidence, and reflect on their findings as a means of exploring questions that they have about phenomena in the world. However, while many researchers are now developing learning contexts more suited to inquiry, few existing curricula (e.g. textbooks) provide truly open-ended inquiry (Germann, Haskins, & Auls, 1996).

Creating curricula to foster student inquiry is challenging in part because the process of scientific inquiry can be difficult for students. Students who engage in inquiry often have trouble designing experiments to evaluate alternative hypotheses, and have trouble using data to support their arguments (Klahr, Dunbar, & Fay, 1990; Kuhn, 1993; Schauble, Glaser, Duschl, Schulze, & John, 1995). Further, the purpose of scientific inquiry can be opaque, as students often view what they learn in science class as unrelated to the way things work in the real world.

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One promising approach to incorporating inquiry into high school science classrooms lies in situating authentic inquiry within an engineering design context. Design is attractive for several reasons. First, it is an appealing domain, where students have the opportunity to apply scientific understanding to solve real world problems. Second, design creates opportunities for students to engage in inquiry in order to learn about factors that can improve their designs. Here, the explanations which students pursue relate to the behavior of their designs; in particular, how the structure of their design affects its function. The result of their inquiry can inform later designs. Design problems rarely have one right answer, which allows students to pursue multiple alternatives and argue for the strength of their own design.

The testing of designs generates data that students can use to compare different designs and reason about design performance. For example, students building model fishing poles from composite materials can explore how different materials and methods of combining materials affect properties such as the strength, stiffness, weight, and cost of their designs.

Finally, the iterative nature of design tasks creates a natural cycle in which engagement in inquiry during one cycle yields information that students can apply when they redesign their product.

Engineering design and scientific investigation

While design offers many opportunities for students to engage in inquiry, it also presents some obstacles. Design is a particular kind of problem solving that possesses its own set of goals. Students engaging in inquiry within a design context are often pursuing goals that relate to engineering as well as inquiry. These goals, and the methods used to attain them, may at times be in conflict.

Design projects have very immediate functional goals which center on design performance. Success can be evaluated by testing a design to see if it meets a set of specified criteria. Students pursuing these goals may adopt a different style of experimentation than the traditional “vary one thing at a time” approach, often “screening” different design possibilities very rapidly as they try to locate a particularly promising design (Baumgartner & Reiser, 1997). This process results in a more rapid exploration of the space of design possibilities, but at the expense of more reliable experimentation that generates evidence to support explanations for design performance. Focusing solely on improving design performance may lead students to pursue design solutions in a haphazard manner, resulting in superstitious design decisions and repetitive testing (Schauble, Klopfer, & Raghavan, 1991).

The purpose of inquiry in design contexts is more explanatory in nature: to understand why a design works. The success or failure of the design itself is less important than the explanation behind the design's performance. The methods focus on investigating the effect of particular design factors, rather than being focused solely on overall design performance. While this form of experimentation may yield better data about certain design elements, it limits the range of design exploration.

Students who engage in inquiry in design contexts are asked to pursue both design and inquiry goals. Although our intent is to engage students in inquiry, the task of producing a successful design is highly motivating and provides direction for student inquiry. A challenge for curriculum designers and teachers is to create a design context that encourages students to develop their understanding of design factors, allows them room to creatively explore novel designs, and supports the process of engaging in scientific inquiry.

A curricular model for inquiry through design

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

- A series of *staging activities* provide students with background ideas, principles, and evidence which they may apply to reason about their design.
- A *design challenge*, which may be posed by the teacher or the students, asks students to propose and build a design to meet a specified need. In addition to the goal of producing a functional design, students are given a goal of explaining why their design works. Students typically build a series of designs in order to evaluate the effect of different aspects of their design.
- The final component is *iterative redesign*, where students apply what they have learned from both the staging activities and their initial design efforts to improve their own design. An opportunity to redesign allows students to explore alternative designs and then use what they learn to produce an optimal design, rather than targeting an optimal design from the beginning.

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

A principle of the inquiry through design approach is to use the design aspects of the task to motivate engagement in inquiry. Consequently, we expect students to adopt design goals as well as explanatory goals over the course of the project. Our intent is for students to use formal design cycles to investigate specific design factors. For example, students might initially propose several design ideas, not all of which they can build. They choose one or two of the designs to pursue based on which designs they believe will perform the best: a decision based on experience, ideas and principles learned in the staging activities, and perhaps some qualitative evidence that they generate on the spot. When they build their design, they are prompted (by instructional materials or by the teacher) to explore a particular design factor that they believe is important. By building several design variants, the group can evaluate the role that design factor plays in their overall design. When it comes time to redesign, students apply what they learned from this investigation to improve their design, and possibly investigate another factor.

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

Examining student use of evidence in design projects

What is the product of scientific inquiry within design contexts? By providing an avenue for the application of scientific knowledge, design encourages students to engage in investigations to develop their understanding of design performance. If students are building a fishing pole, they might want to know how the use of different kinds of materials like wood, metal, or plastic affect their design. They may also explore how the geometric orientation of these materials affects the design's tensile or compressive strength. The ultimate product of these investigations are explanations for design performance: why does this design work in the way it does?

A critical factor in building explanations of this kind is the nature and use of evidence. The strength of a particular explanation rests on the evidence which supports it; the right kind of data can turn a merely plausible explanation into a compelling one. One measure of students' engagement in inquiry lies in the nature of the evidence they use to build their explanations.

Patterns of evidence use

Over the course of a design project, students may use different kinds of evidence in different ways. For example, the kind of evidence necessary to convince a group member to try building a design may be different from that required to support a written explanation that the teacher grades. Students seeking information to help make a design decision may use evidence differently than they would when making a formal presentation before the class. Student use of evidence may also vary based on where students are in the design process. Students just beginning to brainstorm design ideas are engaged in a very different activity than students who are redesigning their product.

These patterns of evidence use may be characterized by the nature of the evidence as well as the nature of the experimental design. We use the term "evidence" fairly broadly to include any information that a student might use to support a design explanation. Such evidence could range from qualitative data "collected" as part of a thought experiment to quantitative data generated in the lab. Students may also choose to generate evidence about a specific part of their design or about the entire design.

Experimental design refers to the larger framework in which students are gathering evidence. In a more exploratory setting, students might gather evidence about different designs in a linear fashion, as they try one design, then another, until they find a design that meets their performance standards. Such an approach may make it difficult to understand which aspects of design affect performance, if subsequent designs change in more than one way. Students examining the effect of a particular design factor may create a more structured experiment, varying only one thing at a time to generate comparative data that can be used to reason about role of the factor in the design's performance.

As student goals shift from design exploration to scientific explanation and back again, the ways in which they use evidence change as well. Inquiry through design seeks to push students to generate and use evidence in more scientific ways, in order to produce better explanations for design performance. The written curriculum creates opportunities for this kind of use through the framing of the task and through prompts in the design journals. The goal of this paper is to explore the effectiveness of this approach.

What factors affect students use evidence in design contexts?

For students to engage in inquiry in design contexts, they need to be able to produce and use evidence to support explanations for design performance. Patterns of evidence use may be influenced by whether students are pursuing engineering or explanatory goals. Our model of inquiry through design seeks to merge these goals by creating specific opportunities for students to generate and use evidence to inform design.

There are two specific aspects of inquiry through design that we expect will help students move to more explanatory patterns of use. Staging activities provide an evidentiary base that student can draw from during their design project; we would like to see students apply this knowledge to inform their design decisions. In addition, the iterative process of designing and then redesigning is scaffolded so that students treat each design cycle as an experiment, generating new evidence to reason about their design. We are interested in seeing what kind of evidence results from these design cycles, and whether students apply such evidence in their later designs.

Of course, students may be prompted to use evidence for other reasons. While these modules are intended to structure student inquiry in a particular way, they are only one factor that contributes to the design context as it appears in the classroom. The instructional materials, the teacher, and the students all shape the enacted curriculum (Ball & Cohen, 1996). Teachers in particular shape curricular material to try to achieve specific instructional goals, altering the enactment in ways that may be more or less faithful to the original intent of the material. For this reason, we look at the role of the enacted curriculum, not the written, where interactions among students, teachers, and the instructional materials coalesce.

In summary, the questions we address in this paper are:

- Do the components of inquiry through design engage students in more scientific use of evidence to support explanations?
- What other factors in the enacted curriculum contribute to patterns of student use of evidence?

Method

Our study is based on three cases of classroom enactment of design curricula. In each case, the teacher used curricular units from the Materials World Modules projects, units developed around the principles of *inquiry through design* described earlier. Our goal in each case was to explore the nature of students' use of evidence over the course of the design project. Each of the three teachers represented in these cases enacted the design context in a different way. The differences among these enactments help highlight different components of inquiry through design, which contribute to variation in student use of evidence over the course of the projects. Even within a single classroom, the design context varied over the course of the enactment, as the need for design explanations arose in different settings. We consider the environment in which the explanation is produced to determine how specific kinds of scaffolding or feedback, particularly that provided by the teacher, affect the quality of student explanations.

The classroom enactments also differ in that one teacher used a different module, Concrete, than the other two. While both modules were designed using principles of *inquiry through design*, the domain and tasks that make up the module are different. Contrasting these modules provides an opportunity to explore how other factors, such as the nature of the materials or the nature of task, might also affect student use of evidence.

After providing some contextual information about the teacher, the class, and the project, we will characterize student use of evidence over the course of the project, and discuss how the particular context of each classroom enactment helped to shape evidence use.

Data sources

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

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

RESULTS

Laura's classroom: Students focus on experimentation

Background

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

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

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

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

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

Laura felt that for students to successfully create their own experiments, they would need a lot of support. Consequently, Laura provided heavy scaffolding of student experimentation (Baumgartner & Reiser, 1998). She framed the task as a series of experiments, and used an assessment measure that did not reward students for design performance. She also toured the room frequently, visiting groups and using these interactions to coach students through their experimental design.

Student use of evidence

Student use of evidence in Laura's class was strongly shaped by her focus on experimental design. For example, in their initial design, Sarah's group varied the amount of telephone wire they used to reinforce their straw, producing five designs that ranged from two straw lengths of wire down to one quarter straw length of wire. Since the group was focused on exploring the effect of the wire, they made no other modifications to their design. What they learned from their experimentation was that the two lengths of wire, which were about as much as would fit inside the straw, produced the strongest and most flexible design. Although the students predicted that this design would be the strongest, the fact that it was most flexible surprised them. In their redesign, they built on this data by using this design as a starting point, as they explored which aspect of the wire was contributing to the design. (Telephone wires are comprised of four smaller wires, each sheathed in plastic, surrounding by a larger plastic sheath.) They again limited their variation to amount of telephone wire, but varied the number of smaller wires on the grounds that the extra plastic in the big wire was limiting flexibility. In both instances, the group's experimental design results in evidence that support their explanation of design performance.

While the group generated useful data about their design and redesign, they did not explore many alternatives, and did not take advantage of evidence from earlier staging activities. Sarah, Kelly, and John made only three major design decisions over the course of their project, and reached early consensus in each case. It may be that Laura's framing led to an immediate experimental focus, and students never had a chance to engage in more exploratory investigation.

Renee's classroom: Students explore many design options

Background

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

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

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

For their initial designs, students were instructed to build at least three prototypes that varied in some way. After these designs were tested, groups wrote on the board whether or not their variable helped their design. For their redesign, students then drew from their own results, as well as what was on the board, to create a new design that optimized strength and flexibility while minimizing mass.

Student use of evidence

Students were told to vary something in their design, but Renee did not provide much scaffolding for experimentation, preferring to let her students work things out for themselves. (A goal of Renee's was to foster more independent work in her students.) Ellen's group considered many materials before deciding what they would build, including several materials from the earlier strength and stiffness activity as well as materials they and other groups brought in from home. Many of the decisions made about the use of these materials were based on qualitative testing of individual materials. If the students could get their hands on the material, they could test it, flexing it experimentally in their hands to get a sense of the material's strength and stiffness. These qualitative tests provided an initial round of screening before students settled on their first official design: a straw reinforced on the inside by a plastic rod and four wires, and reinforced on the outside with duct tape. The choice of duct tape was based on data from an earlier activity, which had shown that the geometric alignment of fiber-reinforced tape helped make a foam beam more stiff.

One early design idea that divided the group was the use of modeling clay as a means of reinforcing the inside of the straw. Ellen proposed the idea, which Lisa and Carol both considered a waste of time. However, Lisa and Carol could not convince Ellen that clay would not work; the students simply differed in their beliefs about the effectiveness of the material. The students could not qualitatively test the clay because the task of packing the clay inside the straw was itself a challenge. Ultimately, Lisa and Carol realized that to convince Ellen, they would have to help her construct the design, so that they could use the results to support their argument. (In the course of helping Ellen to pack the clay inside the straw, all three students decided that regardless of the clay's reinforcing properties, it was just too difficult to pack it inside the straw, and moved on to another idea.)

The group's formal testing of their design did incorporate a variable, but seemed more like a series of redesigns than a planned experiment. The group had come up with a design that had several elements: four wires and a plastic rod on the inside of the straw, and duct tape around the outside. After testing this design, they replaced the wires with a short fiber optic cable, and their third design swapped the cable for a wooden skewer. Thus, their variable was essentially whatever was inside the straw along with the plastic rod; the rod and the tape remained constants.

The group had several difficulties aligning evidence with an explanation for their design, which ultimately led to confusion about how each aspect of their design affected its performance. For example, the students felt that the plastic rod was an important part of the design, yet they never tested its effect by removing it from their design. In an interview following the project, Lisa describes some of the group's confusion, and how they rapidly moved from one idea to another in search of better materials.

LISA Well, we... I'm not sure that we really knew what did work and what didn't work. We, we thought that something worked better than another. Like, we thought the plastic worked well at first, but... and we thought the wires didn't work. And, yeah, the wires... and, um, wires aren't good because they don't bounce back or anything and I don't think the plastic worked overall because it wasn't really strong enough and after a while of bending up and down it didn't bounce back totally and it became weaker. And, um, and so the fiber optics seemed good and it seemed like it had the right properties but in the end I don't think it came back either. I think it weakened too, because it's... I think it's plastic, but it's different.

...and the duct tape seemed good, but we wanted something that would work like the duct tape except better, so... I'm not sure if the tape did anything or not, it may have just been there and we just, it just didn't work.

This group displayed more of an exploratory approach to their design, trying to incorporate multiple ideas into a single design. This made it difficult for them to generate evidence that spoke to the effect of a single aspect of the design.

David's classroom: Students combine exploration and experimentation

Background

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

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

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

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

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

While David told the class that they should vary something in their design, he didn't spend much time coaching them through this process; he was more concerned with helping students address the pragmatic challenges of their designs, such as building molds in the shape of bats, shoes, pots, and other objects that the students decided to make.

David also wanted students to be able to use evidence from earlier activities within the design project. To make it easier for students to do this, he had them document their results from the earlier activities on large pieces of butcher block paper, which were hung in the back of the room where students could easily view them. David also made a point of suggesting to students during the design process that they might benefit from using the evidence they collected earlier.

Student use of evidence

Two aspects of this project changed the way students approached the task: the availability of data from earlier staging activities and the fact that there would be no redesign. While students in this class picked several different objects to design, including baseball bats, bocce balls, and holiday ornaments, students decided in all of these cases to include strength among the various properties their object had to possess. This made the earlier staging activities, in which students measured the strength and brittleness of different mixes of cement, water, and aggregate, highly relevant.

Students took advantage of this data. For example, the group that made bocce balls drew on their earlier tests to help them come up with five different design variants. They described their reasoning this way:

> The first 2 samples were the same measurements as the 2 strongest concretes from the previous reinforcement activity. We figured that being strong was less important than being less brittle. The balls would need to withstand impact, so it didn't matter if the ball was strong if it were very brittle. So all of our samples had a lot of water in them.

While the first two variants were taken directly from the earlier activity, the others were used as opportunities to explore other ideas.

> Our third sample was just sort of an experiment to see what would happen to the ball if there was 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.

Students in David's class had only one opportunity to test their designs: they did not have a redesign, and it's impossible do the sort of rapid iteration that Renee's students did when you're working with a material that requires days to cure. As a result, students used the variations in design for exploration, rather than for tight experimentation around a single factor.

DISCUSSION

Student use of evidence varied across the three classrooms, which is not particularly surprising considering that each enactment of inquiry through design varied as well. The difference between David's use of the Concrete module, and Laura and Renee's use of Composites, may contribute as well to variation in evidence use.

We will discuss the role of inquiry through design in shaping student use of evidence, as well as other factors which emerged over the course of our observations.

Inquiry through design and student use of evidence

Staging activities as sources of evidence

Student use of evidence from staging activities to inform their design decisions was most pronounced in David's class, where most groups based their design's mix ratio on the results of an earlier activity. There are several reasons why this class was so successful at drawing on this evidence. First, the data was directly applicable to their design. Although each group chose its own object to design, most decided to base the performance of their design at least partially on strength or brittleness, two factors that they tested in the earlier activity. Since the materials and the desired properties were exactly the same, the value of using this evidence was obvious. In contrast, students in Laura's and Renee's class produced less evidence in the staging activities that could directly inform their designs. Although the staging activities stressed the same properties (strength and flexibility) as did the design project, the materials used in the earlier activity did not transfer over the design, because the physical shape of the design (a narrow cylinder) differed substantially from the foam beam activity (a larger rectangle).

David also took care to help students to use the evidence from the earlier activity in their design. Student results were compiled on large sheets of butcher block paper, which were hung in the back of the room so that students could easily access them. David suggested that students look at these results during the start of the design project.

Finally, because students in David's class did not do a redesign, they had only one opportunity to consider existing evidence before committing to a design. Further, concrete, unlike wood skewers, plastic rods, and straws, is not amenable to qualitative testing during the design process; students had to wait for their concrete to set — a multi-day process — before they could get feedback on their design's performance. It may be that students took advantage of earlier evidence because it was the only data available that would inform their design.

Design cycles as contexts for experimentation

Each class used design cycles as opportunities to build a set of design that varied in some way. Of the three classes, Laura's was the most consistent about varying only one aspect of the design. This resulted in evidence that directly informed their understanding. Student success using the design cycle as an experiment was due largely to the tight scaffolding that Laura provided. Students had to commit to a design proposal that included a specific variable before they began building their designs. The immediate focus on experimentation limited the amount of time student could have spent qualitatively exploring the domain.

David's class did not do a redesign, and so did not have a chance to apply what they learned from their designs. However, they did try to explore different design ideas within the scope of a single design cycle, and did try to improve on the mix ratios that were used in earlier activities.

Renee's class was in many ways the most interesting of the three in the way students used the design cycle to produce evidence. The observed group did vary one thing about their design at a time, but did so by testing a design, then varying one thing, testing the next design, varying another thing, and so on. Essentially, this group did a series of redesigns, drawing on what they learned from the single object that was tested each time through. Although this approach allowed the group to learn from each iteration, they ultimately lost track of what they were testing, and had to go back and create a new experiment where they tested a series of designs in parallel. The group also created more complex designs than Laura's students, and while they varied one particular aspect of their design, by the time of their interview they were ascribing design performance to other, untested aspects of the design.

The role of written prompts

We were interested in exploring the role that written prompts in the design log sheets played in shaping student inquiry and use of evidence. We found that the use of the prompts varied in different classrooms. Laura used the log sheets and encouraged students to document their work as they went. David handed out the log sheets and suggested that students use the prompts as a guide, but did not require it. Renee chose to have her students use their own lab books, which did not contain prompts, and she did not present students with specific prompts until the final day of the project.

Students using the written prompts in Laura's class did appear to structure their experimentation to produce useful evidence, but it is difficult to separate the role of the prompts themselves because Laura visited each group regularly to discuss their work. At the very least, the prompts served as objects around which Laura could build her scaffolding for student inquiry.

Other factors

The role of the audience

In general, students did not feel that strong evidence was necessary to support their design decisions, as long as they themselves believed that the design would work. For example, decisions about many early design decisions turned on evidence that was qualitative at best, such as descriptions of how a material like a pipe cleaner would perform under a load. Such informality in the use of evidence at this stage is consistent with a design goal of finding reasonable solutions quickly; formally testing materials takes time, especially if the students already believe they know what the material does.

Our results suggest that student use of evidence is driven in part by the audience for the student's explanation. If the audience is the student, as in the case of using evidence to support design decisions, evidence use is often incomplete. While students often present plausible explanations for which component made the biggest difference, their use of evidence leaves their results open to alternative interpretations. But since students are unlikely to question their own explanations, this use of evidence remains unchallenged.

It was only when external actors questioned the plausibility of their design that they would focus on producing evidence to support their claim. Renee's students' argument over the role of modeling clay in the design is one example of the kind of escalation that can occur when students find themselves in disagreement over design decisions. Ultimately, these students realized that they would only be able to convince their peer by building and testing the design idea, which they then proceeded to do.

When presenting explanations to peers and teachers, students used evidence in a more comparative way, citing the results of multiple variant designs to show the effect of specific components within their design.

The nature of evidence as a constraint on explanation

Design projects such as these, where students are designing artifacts comprised on multiple materials and where students test these artifacts in multiple ways, produce evidence that constrains student explanations in certain ways.

For example, testing completed designs makes it difficult to evaluate the effect of specific design factors, unless those factors are controlled over a range of design variants. When students do control variables systematically, as happened in Laura's class, they can produce evidence that helps explain the effect of certain design factors. Students may test individual materials prior to incorporating them into their design. This happens frequently, and is well illustrated in Renee's class, where students engage in animated discussions about the role that specific materials will play. However, these mini-experiments with individual materials were never performed in a systematic, quantitative way. We believe that this is due primarily to the way the design task is presented; students are never asked to test individual materials, only the design as a whole. (On the other hand, the staging activities that precede the design project provide opportunities for students to explore individual materials. However, these materials are not always used in later designs.)

The role of the materials themselves was particularly apparent in the contrast between David's use of the Concrete module and the other teachers' use of Composites. Because concrete cannot be tested quickly, since mixes must set for a few days, students cannot engage in rapid iteration through design ideas in the way that students using composite materials can. This difference changed the focus on the design project, since students had to look elsewhere — the staging activities — for evidence that could inform their design. It also led students to try to milk each design cycle for all they could, combining multiple experiments within a single set of design variants.

Another concern with these specific design projects is the depth of the explanations that students generate. We noticed the student explanations for design performance, even when based on supporting evidence, often lacked causal depth.

In these activities, students use materials such as wood, metal, plastic, and fiberglass to reinforce a composite. While student-generated evidence may support a claim that reinforcing a composite with metal is better than reinforcing a composite with wood, the explanation for such a claim is often simply "metal is stronger than wood, so the metal-reinforced design is stronger than the wood-reinforced design." Many student explanations rest on the inherent properties of materials (e.g. the strength of wood, the flexibility of plastic) and the design context lacks the support to help students explore why these materials have varying properties.

SUMMARY

Design tasks are promising contexts for inquiry. However, the process of design carries its own set of goals, which must be addressed if design is to be used as a means to another end. While design projects capture student interest, require students to design their own experiments, and provide suitable data students may reason with, the engineering nature of these tasks—to produce better performing designs—may interfere with students' generation and use of evidence to produce better explanations for design performance.

Successful design is not always informed or driven by precise scientific inquiry, nor do we expect students who participate in these design projects to always turn to scientific evidence before making any decision. Rather, we seek to understand the different ways in which students use evidence in this setting, in order to understand when and how evidence is needed and how we can scaffold student generation of evidence-backed explanations for their designs.

The various components of inquiry through design seemed to afford student attention to evidence, but only in specific cases. Staging activities provided evidence for students to reason with during design, but were only consistently used when the relevance of the evidence was obvious, as was the case in David's class. Using design cycles as an opportunity for experimentation worked, although student experimentation was better in Laura's class, where there was a greater degree of scaffolding during the design process.

Other factors that influence student use of evidence included the nature of the audience for student explanations as well as the nature of the design materials themselves. One of the concerns we have is that students do not see a need for evidence to support design decisions that they believe will be effective. Often, it seems a disbelieving audience serves as the trigger to focus students on generating evidence to support their explanation.

The written prompts were only used in one of the three classes, and Laura's scaffolding made it difficult to separate the role of the prompts from her own. The wide variance in use of the written prompts underscores the importance of the enactment in student use of evidence. As curriculum developers, we are exploring means of incorporating information for teachers about these issues into the curriculum itself, so that teachers may be better prepared to enact design projects in ways that support inquiry.

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