



Evaluate-and-Redesign Tasks: Using Interviews to Investigate How Elementary Students Iterate (Fundamentals)

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Iteration is a goal-directed activity¹ that involves making incremental refinements during the development of a design solution. A dependence on iteration to optimize solutions, along with considering trade-offs and constraints, is one of the distinguishing factors between the processes of engineering design and scientific inquiry². Iteration has been studied extensively at the college and expert level, and linked to better problem understanding and design quality^{3,4}. However, there has not been enough research to inform our ideas of how K-12 students engage in design iteration within engineering challenges. This paper will describe part of a larger study on design iteration in elementary students, wherein groups of students (Kindergarten and 3rd-grade) participated in clinical interviews with the task to analyze and redesign solutions to an engineering design challenge. The goal of these interviews, inspired by Crismond's^{5,6} investigate-and-redesign (I&R) tasks, was to observe how students considered multiple variables and constraints in the context of a given design solution, and applied their observations to redesigning the solution. The interviews are described as analyze-and-redesign tasks because much of the "investigate" work was completed in the classroom; the modified interviews included asking the students to observe two design solutions, list their pros and cons, choose the best design solution, and redesign the less optimal solution to better meet the challenge requirements. The results of this study have implications for designing and assessing engineering design lessons with young elementary students.

Previous Research

With the advent of STEM education, topics in engineering and technology have been added to the traditional K-12 science and mathematics frameworks and standards.^{7,8,9,10} Many standards present engineering design as a sister process to science inquiry.^{10,11} Engineering design, as an integral part of every engineering discipline,^{3,12} is a natural way to introduce students to the practice of engineering while integrating learning from other subjects. However, according to the National Academy of Engineering's 2009 survey of K-12 engineering research and literature,² there are several gaping holes in what is known about how students think about and do engineering. They found: "no widely accepted vision of what K-12 engineering education should include or accomplish" (p.7); no attempt within the research community "to specify age appropriate learning progressions in a rigorous or systematic way" (p.8); and a lack of research characterizing what engineering-design skills K-12 students already possess. The NAE report seems to suggest our current implementation of K-12 is haphazard, and in their opinion, we are operating with scant knowledge about our students' understanding of engineering and the design process.

More recently, Crismond and Adams' *Informed Design Teaching and Learning Maxtrix*¹³ conducted a meta-literature review of design studies, culminating in the creation of an integrative framework of student skills and teaching guidelines. However, their assessment of "beginning" designers is tied to experience, not age, and although the framework is intended to cover K-16, many of their examples come from college classrooms. We cannot assume a Kindergartner will undertake the process of engineering in the same way as a Freshman in college, even if both are

novices to the field. Indeed, the NAE notes the lack of research at the elementary-school level, particularly at the younger grades (K-2)².

But even narrowing the focus down to early elementary students, as in this study, engineering design is very broad topic for research. Crismond and Adams' *Matrix*¹³, for instance, identifies nine *Design Strategies*, called design activities in this analysis, in which students engage while designing. Out of these, the *Revise/Iterate* activity proved promising for two reasons. Iteration is a goal-directed activity that involves making incremental refinements during the development of a design solution. A dependence on iteration to optimize solutions, along with considering trade-offs and constraints, is one of the distinguishing factors between the process of engineering design and scientific inquiry.² This is important in the context of STEM education to ensure that science inquiry and engineering design are represented authentically, as epistemologically related, but distinct, problem-solving processes. Secondly, as students iterate through a solutions to a problem, their understanding of the problem also evolves,¹ and studies suggest that a higher rate of iteration in college-students' design corresponds positively to solutions' quality.³ Additionally, experts and senior college students have been found to cycle through design iterations more frequently than college freshman, further supporting the idea that more iteration leads to better design solutions.⁴ However, neither Crismond and Adams',¹³ in their meta-study, or the National Academy of Engineering report², found research to cite on iteration at the elementary-school level. Thus, studying iteration in the engineering design behavior of elementary students should shed light on unexamined ways teachers can help their students iterate to achieve better solutions to design problems.

However, clinical interviews including I&R tasks have the potential to shed light on how students engage in design strategies, including redesigning. Investigate-and-Redesign (I&R) tasks were developed by Crismond⁶ as a science-oriented complement to more technology-education-aligned design-and-build tasks. The steps of Crismond's I&R tasks included "messaging about" with devices, explaining how devices work, designing experiments to evaluate devices, and redesigning devices.⁵ Much of the work of professional engineers is improving and redesigning existing products, therefore I&R tasks have the potential to be as authentic as activities where students design from scratch. For beginning designers, providing a scaffolded series of tasks, like an I&R task, may help avoid feelings of frustration encountered when first attempting design work,¹⁴ and allow students to complete a design cycle in a fraction of the time as start-from-scratch designing. Additionally, I&R tasks provide the potential for teachers to observe students engaged in engineering design practices outside of the classroom. Individual teachers implementing design lessons in a classroom will be unable to follow the design trajectory of every group of students over the course of several days. Indeed, between monitoring the testing station and stewarding student groups, three or four teachers and assistants seemed ideal. If a teacher is interested in following up on their students analysis and redesign strategies after participating in the design lesson, short I&R tasks completed in a group interview have the potential to be an economical solution.

Crismond's analysis of the I&R tasks focused on the subjects' application of scientific concepts to analyze and describe the devices with which they were presented, as well as to investigate the process skills of naive, novice, and expert designers as they redesigned those devices.^{5,6} In this research, the focus has been narrowed to how students identify and reason about scientific

variables and the specifications/constraints of the engineering design challenge. The design and re-design of engineering solutions are governed by the requirements of the problem and the constraints of the system. According to the *Standards for Technological Literacy: Content for the Study of Technology* (ITEEA),⁸ engineering design is purposeful, with the end-goal shaped by *specifications* and *constraints*. Specifications tell the engineer what the design needs to accomplish, and constraints are factors—such as cost, size requirements, and availability or physical properties of materials—that place limitations on design. What does this have to do with iteration? To initiate a redesign cycle, the students must first be dissatisfied with their design. Does it meet the specifications? Are the tradeoffs optimized? Are there other requirements and constraints not defined by the initial problem that should guide the design? Are the constraints of the problem restricting the design I wish to implement? Through I&R tasks, Crismond guided his subjects in evaluating existing devices, defining the ideal properties of such a device, and proposing an improved design of the device. These activities necessarily involved specifications, constraints, and scientific variables.

There is a body of research on scientific reasoning about variables, and much of it focuses on very young people (for a good review see Kuhn, Garcia-Mila, Zohar, Andersen, White, Klahr, and Carver, 1995). The period between the age of 4 and 8 is one of significant development of basic metacognitive competencies that serve as underpinnings for more complex forms of reasoning about scientific variables.¹⁵ Determining the relationships between variables and scientific theories requires conducting a series of experiments in which those variables are isolated, or controlled for. Judgments of comparisons are a precursor to the control of variables strategy that emerge during the elementary-school years.¹⁵ As Kuhn explains, young students are first able to compare individuals ("Can I run faster than my brother?"), and later groups of individuals ("Can the girls in the class run faster than the boys?"), and then with considerations of fairness ("What if the boys wore running shoes and the girls' didn't?"). From there it is not a great leap to formalized comparisons with the framework of a controlled test of covariance between variables (e.g. gender and running speed).¹⁵ Likewise, in Crismond's I&R tasks, subjects were asked to compare and critique several devices, and optimal analysis and redesign depended on a fair, formalized assessment of the performance of each.^{5,6} Although they do not necessarily do so spontaneously, students as young as age eight can be taught to carry out controlled scientific experiments; one could imagine them comparing the products of engineering design as well. Pre-school students are able to choose from examples tests that will control for variables to reveal covariance,¹⁶ and elementary-school students can be learn how to control for variables during inquiry both by direct instruction, and repeated, sustained exposure.^{17,18}

While many studies have examined whether students can identify the causal and non-causal variables in a system, fewer have focused on the subsequent task of predicting and reasoning about the interactions between variables and those effects on the system.¹⁹ This skill, called multivariable prediction by Kuhn, is notoriously difficult for adults, let alone adolescents, and is distorted by immature mental models of multivariable causality, causing faulty predictions and inconsistent causal attributions.²⁰ When taken beyond a contrived, controlled context of research and situated within real world scientific or engineering problems, the variables and their effects multiply to a complex web of relationships that often takes the power of super-computed models to untangle.²⁰ The goal of engineering design is slightly different than scientific inquiry, and it is inefficient and sometimes impossible to hold some variables constant while manipulating the

other. Designers must also deal with tradeoffs, which require not only that the relationship between two variables is identified, but also optimized to produce the best results. While the evaluation and testing phase of engineering design utilizes experiments much in the same way science does, the role of variables in designing and redesigning is more complex.

Research Question

With this analysis of student interviews, including Evaluate and Redesign (E&R) tasks, this analysis will answer the following question: How do young elementary students consider variables, specifications, and constraints when evaluating and redesigning solutions to engineering design problems?

Methodology

The study's subjects were six Kindergarten and nine 3rd-grade students at a public, magnet elementary school in a large, urban school district. The school's demographics were representative of the state and district averages, and the school had recently been named a STEM school by the district, which meant that it was expected to integrate STEM across all subjects, and provide students with increased opportunities for engaging in STEM activities such as science fairs and university/industry partnerships. Even before this designation, the school employed an engineering coach who saw students periodically in a manner similar to music or gym classes. The students' teachers were participating in a longitudinal professional development program designed to help them design integrated STEM lessons for their own classrooms, led by the author and the Center for Engineering Education and Outreach at Tufts University. For choosing the students, a purposeful, maximum variation sampling was employed.^{21,22} The teachers selected from students who had complete consent and assent for video-recording, interviewing, and sharing of data, and who were not chronically absent, so they could be followed across lessons during the school year. The students represented a diverse sample of ethnicity, gender (parity), and academic ability.

All students participated in two engineering design lessons in their classrooms, one utilizing LEGO materials, and one utilizing common craft materials. Lessons were co-designed by the author and the classroom teachers to encourage iteration, and match Crismond's recommendations for good engineering design challenges (Fig 1).⁵

1. Authentic, hands-on tasks
2. Familiar and easy-to-work materials using known fabrication skills
3. Clearly defined outcomes that allow for multiple solutions
4. Student-centered collaborative work and higher-order thinking
5. Allow for multiple design iterations to improve the product
6. Clear links to limited number of science and engineering concepts

Figure 1. Crismond's (2001) summary of features of a pedagogically solid design task.

In our case, engineering design challenges were sometimes integrated with science concepts (human anatomy, plant biology), but also with mathematics (graphing, measurement), and literature (folk tales). After the first lesson had been completed in each classroom, the students

were interviewed in their original groups following a revised protocol based on Crismond's I&R task^{5,6} (see analysis section, Figures 4 and 5, for interview protocols), and the task was based on the design challenge from this first lesson. Whereas the I&R tasks began with an "investigate" stage, the students had much experience "messing about" with the materials, constraints, specifications and variables as they were attempting to meet the design challenge with their own solutions in the classroom. Additionally, testing protocol had already been established during the classroom lesson, so students were not instructed to devise experiments to test their solutions during the interviews. This left the following activities for the modified tasks: recall the design challenge from class and all the specifications, given two solutions to the challenge analyze how well the solutions met the challenge, categorize one of the two solutions as "best," and redesign the one that is not the best solution. Subsequently, these interviews can be described as evaluate-and-redesign tasks (E&R).

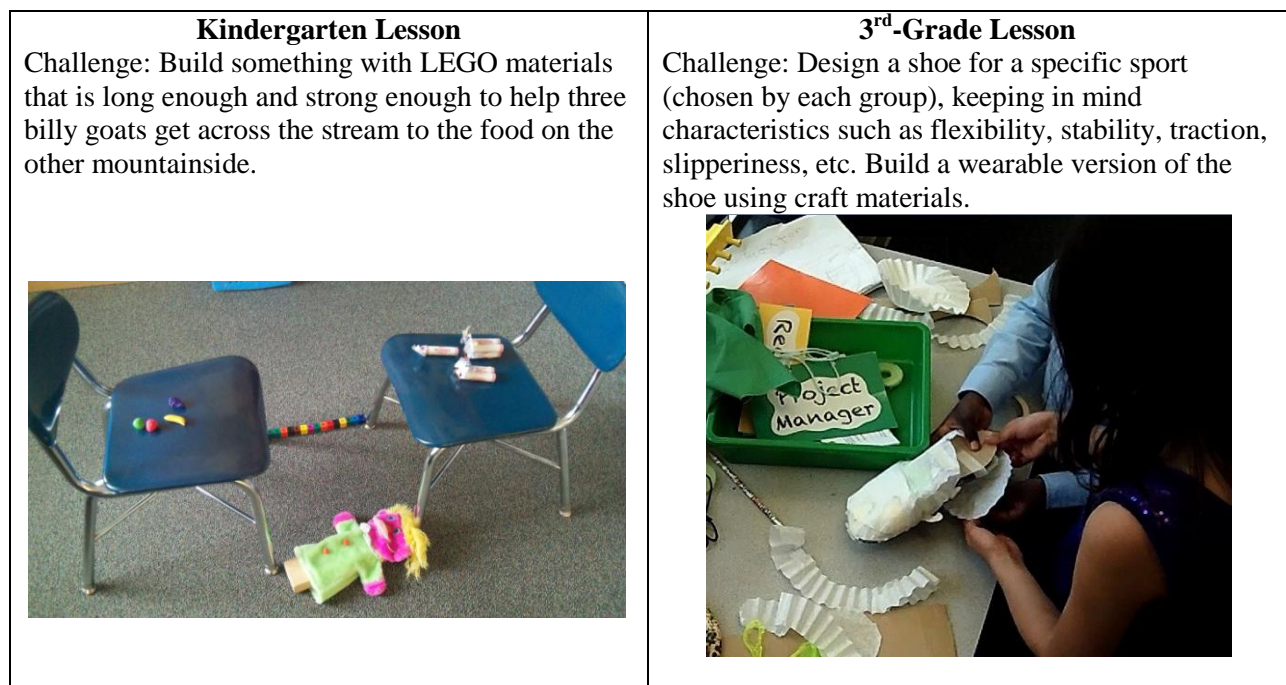


Figure 2. The classroom engineering-design lessons upon which the interviews were based. The picture on the left shows the testing station with representations of the mountains (chairs) and the goats (rolls of pennies). The right shows students constructing a shoe from cardboard, foam, coffee filters, and tape.

Students in the Kindergarten classroom were asked to engineer something, using one LEGO Simple Machines kits, that is long enough that the billy goats can go from one side of the stream to the other side, and strong enough that it will hold the billy goat. The lesson was designed to tie into literature, with the folktale of the Three Billy Goats Gruff, but also with a mathematics unit measurement. As such, the teacher and researcher designed requirements and materials for the lesson very carefully to ensure that students explored the dimensions of weight and length, and also had to make very careful use of their resources. The testing station consisted of two chairs, with a gap in between the bridges must span, and a small, medium, and large goat represented by one, two, and four rolls of pennies, respectively. In the 3rd-grade classroom, students were asked to select a sport, and design a shoe with appropriate characteristics for that sport (from a guided

worksheet, including stability/flexibility, and slipperiness/traction). After completing the worksheet describing the characteristics of their shoes, the groups first planned their shoes on a large sheet of paper, and then constructed the shoe from common craft materials (including ribbon, cardboard, foam, plastic, and tape). See Figure 2.

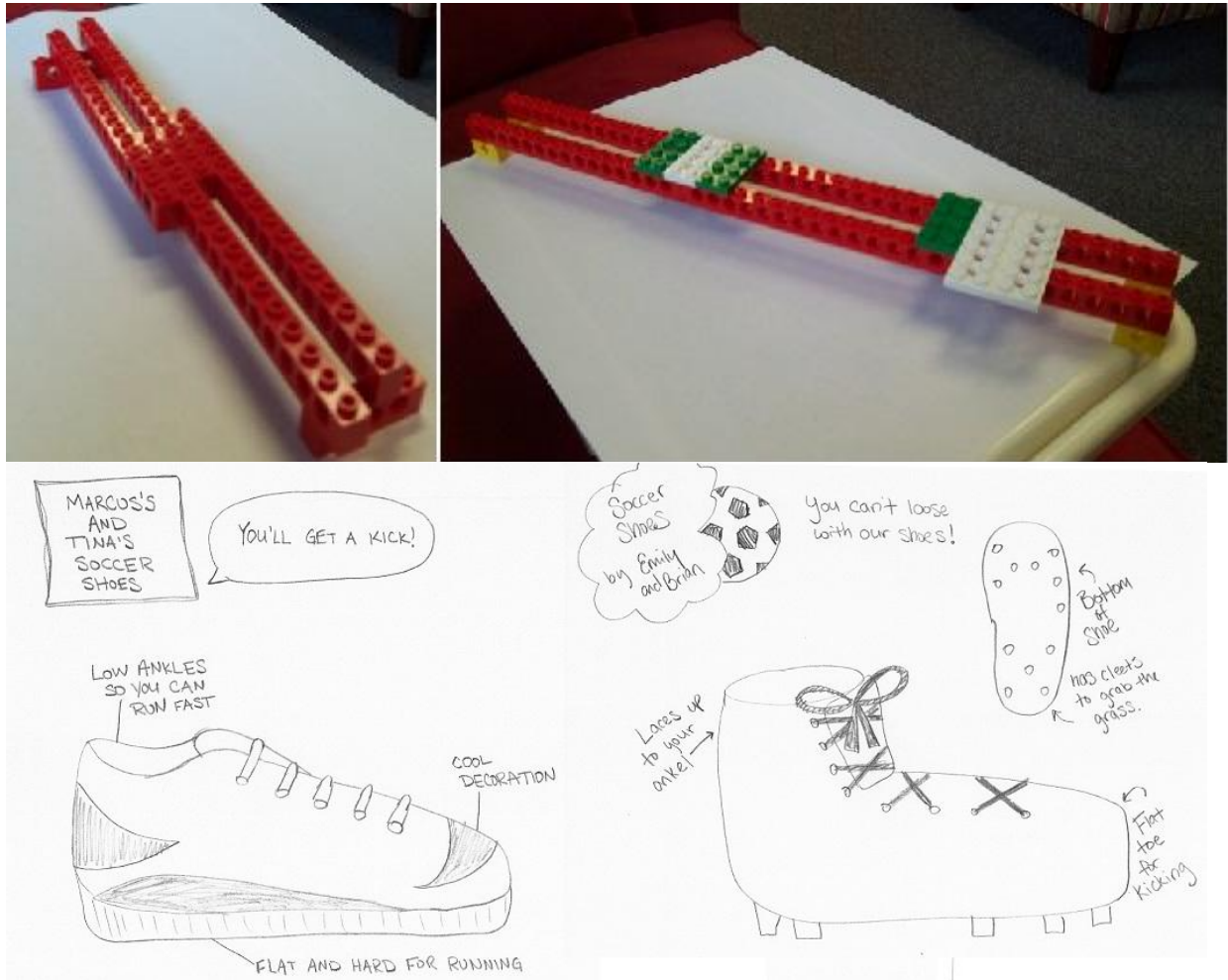


Figure 3. Two example devices for each set of interviews. Top: Two bridges for the Kindergarten interviews, one strong and short (left), and one long and weak (right). Bottom: Two soccer shoe designs for the 3rd-grade interviews, one with low-tops and no cleats (left), and one with high-tops and cleats (right).

For each set of interviews, the two design solutions presented to the students were generated by the researcher, in a style comparable to student-generated solutions, to meet one of two design requirements (see Figure 3); for instance, in the Kindergarten bridge-design challenge, one bridge met the length requirement, but not the load-bearing requirement, and the other vice versa. For the 3rd-grade shoe challenge (soccer was the chosen sport), one shoe possessed cleats to make the shoe stick in the turf, but featured a high-top that immobilized the ankle; the other shoe lacked cleats but featured a low-top, allowing for mobility. The lack of a 'right or wrong' design allowed the investigation to focus on the students' thinking during evaluation and redesign, rather than their correctness. When asked to redesign one of the solutions, the

Kindergarten groups were given a LEGO Simple Machines kit as their construction material, just as they had worked with in class. Kindergarten students did not use paper to sketch or plan their designs before building during the classroom lesson, and it was anticipated that asking them to do so for the interviews would produce unsatisfactory results. Working with craft materials in the 3rd-grade class, however, proved very time consuming and not as conducive to redesign (once you glue or cut, you cannot un-glue or un-cut). Therefore, the solutions presented to the 3rd-grade groups were annotated sketches. For their redesign, each student was given a copy of the design solution sketch, and blank paper to record their new solution. This is most similar to Crismond's protocol.⁵ However, Crismond noted that not allowing his subjects to build was a weakness of his study, because building affords feedback from the materials which informs their design, and possibly prompts even further iteration.

The interviews were conducted by the author approximately a month after the end of the lesson. Students were video-taped, and the videos transcribed. Open coding was used to identify several major themes regarding the students' evaluation of the solutions, and their attention to any variables, specifications, or constraints when engaged in redesigning. The results are presented as two case studies below.

Analysis

The Kindergarten Interviews

1. Can you tell me about the bridges you built in class for the Three Billy Goats Gruff? What did the bridges have to do?
2. Here are two bridges children in a different classroom built to help the Billy Goats get across the stream. You can look at them and touch them.
 - a. What can you tell me about these bridges?
 - b. What is good about this bridge? What is good about the other bridge?
 - c. What is bad about this bridge? What is bad about the other bridge?
3. Which bridge do you think is the best bridge? Why do you think it is the best?
4. Ok, so this bridge isn't the best bridge. Can you think of how you would redesign it to make it better? Here are some LEGO bricks, and a Billy Goat, and two chairs.

Figure 4. Kindergarten Interview Protocol

When asked to recall the specifications of the original bridge-building challenge, 2/3 of the groups listed length, and 2/3 listed strength/sturdiness, which were explicitly stated in the challenge. However, students also recalled some *emergent constraints*²³ which were generated as the students produced solutions in class. Some were practical, to keep the rolls of pennies that served as goats from rolling off, or that the goats had to have some surface to stand on. One group recalled height as a specification, which was a feature they added to their bridge to increase the distance between the goats and the troll. Some students excelled at evaluating the two example bridges, while others could only really comment on the length, or whether the goat (roll of pennies) would sit on the surface without falling off. When asked to evaluate the bridges, One girl included that she was concerned that the rolls of pennies no longer had the paper goat faces as they had during class. One group used vague language, calling one bridge "smaller" and one "bigger," instead of long and short. They also noted that one bridge used more bricks and had more colors in it. The group of two boys conducted the best evaluation of the sample

bridges: they listed how the longer bridge included plates on top to connect the pieces together, and feet on the bottom to help it stay stable on the chair; and how the short bridge was specifically "too short," and needed railings to keep goat from falling off, but seemed sturdy enough (they were the only group to mention this). During their evaluation, they handled the bridges, and noticed that the long one kept falling apart (and therefore was not as sturdy). They were the only group to address every variable explicitly listed in the original challenge, and those which emerged practically from experience during class.

When determining the best bridge, the students disagreed in each group; one would choose the long bridge while the other chose the shorter one. The bridges were intentionally designed so that they would each meet some requirements but not all, and so there was no right choice. Two groups tested the bridges before they could decide on the best one, at which point one student noticed the long one he favored was "wobbly." In another group, one student took possession of the short bridge, calling it "her" bridge, and forgot that length was a specification for the design, stating that it was the best specifically because it was short. After they tested the length at the testing station and hers failed, she agreed that the long bridge was better. In general the students focused on the pros of their chosen designs (one is long, while the other will hold more goats), and were amicable to switching to their partner's chosen design so they could reach a consensus.

In the interviews, students utilized building methods and designs from class, even though it had been a month since they last worked on the design challenge, and even though they were starting from example designs. Especially when at some point students chose to redesign from scratch, their new designs were uncannily like their classroom designs. During redesign, the students attended to the variables and specifications that they recalled from the original challenge, or that they had identified in the example bridges. Sometimes students tried to address variables that the example design already met, such as when one group attempted to make the long bridge even longer. One group mentioned that they should make their short bridge longer, but did not attempt to do so until it failed the first round of testing. All of the students added a surface covering, which both of the examples lacked, for the goats to stand on, and one group attempted to make their first redesign wider, in anticipation for the largest goat. The groups who were redesigning the long bridge recognized its weakness in middle as it broke when they attempted to add and modify pieces. Most attempts to solve this instability were ineffectual. It must be a very difficult thing for students this young to recognize on which axis a design lacks stability, and how to add to the design to address it. Most of the time they added support perpendicular to where the breakage was occurring, even though they claimed their solution was addressing the weakness. After failure, the students were prone to taking everything apart and starting over from scratch instead of basing their design on the previous iteration. One student did not even attempt to fix the example bridge, and instead took it apart and rebuilt it with his own design, even before testing it. Incidentally, that group had the most successful design during testing.

Although the topic was addressed in class during the engineering design challenge, students often used confusing or nonspecific terminology to describe variables and specifications. They referred to the bridge as "big" or "small" instead of long or short, or also used "big" to mean width (necessary for the goats to balance on the bridge). One student alluded to the bridge becoming stronger if they added weight to their design, and another spoke about adding "pressure," although his partner questioned his intent in using that word. The rolls of pennies

used as stand-ins for the goats were occasionally referred to as being heavy, or big. When testing, one group had to be reminded to start with the lightest goat, and not the heaviest one, reminiscent of controlling for variables in scientific experiments, while another group had the forethought to design their bridge wide enough for the widest goat (four rolls of pennies stacked in a square).

All of the groups had a habit of over-engineering their bridges, such that portions of the bridge had redundant supports and were indestructible, but suffered from the instability of one weak connection. One group added length to their bridge even though they knew it was already long enough. Other students ran out of suitable materials using a particular build method before their bridge was long enough to span the necessary gap. Some students asked for additional long pieces, which were not provided in the interest of ensuring the groups considered the trade-offs between length and strength in their designs. One student ran out of LEGO plates to create the surface of her bridge, and so she substituted thicker beams instead. When she discovered that her bridge was not long enough, she was able to connect additional beams to the bridge because of this design choice. How might she have extended the bridge if she had not initially run out of pieces? None of the groups responded with parsimony when confronting shortages of materials.

Sometimes students made changes to their design that should not reasonably fix the problem they encountered. One group tested a bridge which was quite apparently too short (it would not even reach the edges of the chair). However, they returned to the testing station after adding only a few pieces perpendicular to the span of the bridge, which added no length to it at all. After a failed test, one student added a weak section of bridge back to the end of her design and immediately tested it again, with identical results.

Interestingly, only one student mentioned the hypothetical designers of the example bridges while redesigning, saying "we need to do what 'he' did, but make it longer," although for that particular design, the bridge was long enough already. This same student made reference to "planning" what to do next. His partner compared their new design to the previous one they had build in the classroom, noting that in his opinion the new one was better. These comparisons to other designs, and evidence of forethought, are evidence of some metacognitive thinking on the part of the students. It is not surprising that these statements came from the most successful group.

In all, this group had success for the smallest and medium billy goat. Another group redesigned the short bridge to be long enough, but with a structural flaw so that it was not strong enough to support the smallest goat. The last group could not make the long bridge strong enough to support a goat, and upon complete redesign, could not make their bridge long enough to span the gap.

The 3rd-Grade Interviews

When asked to recall the specifications for their shoe design from class, the students' answers were comprehensive, listing all the variables they had been asked to consider and how their shoe design met them. When evaluating the example designs, the 3rd-grade students identified multiple variables to describe each shoe, and were able to generate pros and cons for every

design. One group favorably described a design's cleats, and then critiqued the high-top ankle. Many variables were discussed that had been featured through notation in the example designs, such as the shape of the toe or the cut of the ankle, which had not explicitly been discussed during the lesson in class. Students also generated new emergent constraints, such as the weight of the shoe (lighter is faster, they posited) and the method of fastening (Velcro tape versus laces). The students used very precise language when identifying characteristics of a design, and always provided an explanation to back up their opinions and choices.

1. Can you tell me about the shoes you built in class to play a sport? What did the shoes have to do?
2. Here are two designs students in a different classroom drew for shoes to play [sport]. You can look at them.
 - a. What can you tell me about these shoes?
 - b. What is good about this shoe? What is good about the other shoe?
 - c. What is bad about this shoe? What is bad about the other shoe?
3. Which shoes do you think are the best for playing [sport]? Why do you think they are the best?
4. Ok, so this shoe isn't the best shoe. Can you think of how you would redesign it to make it better? Here is some more paper and pencils, and you can draw on this design, if you want to.

Figure 5. 3rd-Grade Interview Protocol

For all three interviews, all three members of each group immediately agreed on which design was best. One possibility is that this could be due to a preference for one design over another due to the examples not being of equal quality. However, different groups chose different designs as the best example. It is likely the groups were simply responding to the thorough justifications given by students as they discussed the pros and cons of each design characteristic. During these discussions, many connections were made vertically, to concepts of human anatomy and generalizations of the qualities of standard shoes for a given sport, and also laterally, to personal examples from real life.⁵ During their redesign, pros and cons had been described for the example design which they had chosen to modify. However, even as they changed the less favorable characteristics of the shoes, they also retained some of the good characteristics they had identified during their discussions.

Like the Kindergarten students, the 3rd-grade students included variables and specifications identified during the evaluation section in their redesign. Because the 3rd-grade interviews involved only pencil-and-paper designs and not tangible solutions, the students had no feedback or testing for their designs. As a result, they only went through one design cycle. Most groups had lively discussions debating the specifications for their shoes. These did not refer back to their experiences from class, but rather to real-life examples, or demonstrations of the motion of their actual feet, with biological and practical implications. The only talk of materials was from one student who was concerned about not wanting the shoes to get dirty, and another student's talk about possibly padding the ankle for protection. One group spent the whole interview in discussion and hardly documented their design choices on paper. Another group debated their design, and then created a consensus drawing. The last group discussed options as they drew, and generally did not disagree.

Discussion

It is hard to compare the Kindergarten and 3rd-grade interviews because building and drawing are very different design activities, and the study included a relatively small sample size. While the interview tasks would not have been possible with the Kindergartners using pencil and paper alone, the 3rd-graders' analysis of shoe designs was much more thorough in the interviews than in class, where their focus was more on materials rather than the intended characteristics of the shoe. With this analysis of the student interviews, young elementary students have been shown to readily think about redesigning solutions to engineering design problems. Iteration may lead to better designs, as it does with older populations, and students are certainly retaining design concepts from earlier experiences. But as they are emulating those earlier designs, it is hard to say if they modifying them enough to show improvement, and if they are properly analyzing their designs' failures in order to address specific problems

Comparison of example designs and the analysis of potential designs was more developed in older students, which is to be expected developmentally, but certainly not undeveloped in the Kindergarten students. Young children have been shown to be competent in judgments of comparison,¹⁵ evaluating simple if-then rules,²⁴ and applying data to modify theories.²⁵ One worrying aspect of the Kindergarten students' vague description of design characteristics is that in order to properly conduct and analyze test data, students have to be able to properly identify the salient variables. This, and difficulty analyzing the source of failure during testing may have contributed to the difficulties students had in addressing failure in subsequent redesigns. In turn, this may have contributed to their tendency to start over from scratch, rather than troubleshoot. Lehrer et al.,²⁶ in a study of 2nd and 5th-graders, found that students' ideas about structures (in this case, gears in an egg-beater) in the devices and the mechanisms behind them varied between the grade-levels. They point out that even when the structures of a design are visible, and the students recognize the function of an object, children might fail to consider how the underlying structure contributes to the performance of the function.

One of the most interesting findings is that while the Kindergartners disagreed initially on which design was better, the 3rd-graders all reached a consensus on the best design, consistent with their explanations of the designs' characteristics. And while the Kindergartners focused on the pros of each design, which is consistent with predictions from the *Informed Design Teaching and Learning Matrix*,¹³ the 3rd-grade students were adept at recognizing both the pros and cons of the example solutions, and were able to chose the best design despite its flaws.

Conclusion

Developing a better understanding of how elementary students analyze and redesign solutions allows us to better inform the practice of designing appropriate challenges that will encourage iteration and optimization. Kindergartners need much more scaffolding in recognizing variables, constraints, and specifications within designs, and in interpreting the causes for testing failures. This is consistent with the idea valid scientific experiments can be designed and conducted by elementary students, but either direct instruction or sustained experience is required. Further curricular interventions can work on scaffolding testing in a way that is meaningful for the student, but still student-driven.

Much of the group behavior observed with regard to redesign, consideration of variables, constraints and specifications, and general group dynamics matches the analysis done on the video-recordings of these groups designing solutions in the classroom.²⁷ For this reason, E&R tasks and clinical interviews can be expected to authentically capture student thinking and skills for the purposes of teacher assessment. However, the E&R tasks as presented here may need to be further modified to accommodate the difficulties faced by Kindergarten students when having to evaluate a design that is not their own. Additional analysis comparing the classroom and interview data is necessary, and this study is limited in its grade-level scope and sample size. Going forward, E&R interviews could be conducted with extended age-ranges and with more statistically-significant numbers of subjects. Additionally, findings from this study can be applied to curriculum and observed and analyzed in the classroom. Future applications of this work could include developing rubrics to assess students evaluation of designs, and a more detailed exploration of how students use tests and evaluations to inform their revisions of a design.

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