Kindergartners' Engagement in an Epistemic Practice of Engineering: Persisting and Learning from Failure (Fundamental)

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Introduction

Especially but not exclusively motivated by the *Next Generation Science Standards*, engineering has joined more traditional subjects like literacy and mathematics as a part of kindergarten education [1]. The inclusion of engineering in kindergarten brings numerable benefits, including opportunities to apply creativity, learn to work in a team, engage in the hands-on practice of making, explore the designed world, and practice trying and trying again to solve a problem [2, 3]. It is the space between trying and trying again that is of interest in this paper where we explore how 53 kindergartners tested their first try design attempts, were prompted to engage in failure analysis when their designs failed, and planned their second designs.

Background

The Epistemic Practice of Persisting and Learning from Failure

One way to investigate preschool through grade 12 (P-12) students' engagement in engineering is through the frame of epistemic practices of engineering. These epistemic practices represent the ways of knowing and doing that are reflective of professional engineering practice and appropriate for P-12 students. Epistemic practices may also be regarded as ways of doing that are central to the development of an engineering identity. Cunningham and Kelly identified sixteen epistemic practices of engineering from their review of the engineering education literature [4]. In this study, we focus on one of these: persisting and learning from failure.

Within the engineering community, design failure—when a design fails to meet one or more criteria [5]—and the need to troubleshoot and revise designs are normal parts of the design process [6, 7]. Petroski, a prolific scholar of the engineering field and about design and failure, wrote: "Every successful design is the anticipation and obviation of failure, every new failure—no matter how seemingly benign--presents a further means towards a fuller understanding of how to achieve a fuller success" [8, p. 45].

Crismond and Adams [7], citing past work by Crismond [9, 10], described a four-part diagnostic troubleshooting process that informed designers use to analyze and respond to such design failures. The four parts are: observing, diagnosing, explaining, and remedying. First, engineers observe the design during testing, noticing "unexpected or out-of-range behaviors." Second and third, they diagnose (i.e., name/identify) and explain those problems, offering reasons for faulty performance. Fourth, they use this failure analysis in proposing ways to remedy or fix the problems. Crismond and Adams explained that "detected flaws can inspire ideas for simple fixes, additional features, or entirely new and unimagined systems" [7, p. 768]. Comparing the informed and novice designer with respect to diagnostic troubleshooting: (1) the informed designer "focus[es] attention on problematic areas and subsystems when troubleshooting devices and proposing ways to fix them," and (2) the novice designer "use[s] an unfocused, nonanalytical way to view prototypes during testing and troubleshooting of ideas" [7, p. 749].

Research on Failure and Diagnostic Troubleshooting in Elementary School

At the upper elementary level (i.e., US grades 3 through 5; ages 9-11) and through a combination of qualitative classroom observations and analyses of teacher surveys, the first author's previous work has identified a range of both resilient, productive actions and non-resilient, non-productive actions in response to design failures [11, 12]. See Table 1.

Table 1. Summary of upper elementary students' responses to design failure [11, 12].

Resilient, Productive Actions	Non-Resilient, Non-Productive Actions
• Acknowledging design failure when it occurs	• Denying that failure occurred by ignoring proper testing processes
• Trying again	• Giving up or losing interest • Seeing the task as being too difficult
• Engaging in failure analysis	• Making changes to design without planning or thinking carefully
• Focusing on improvement	• Staying with the original failed design
• Working effectively as a team • Seeking help from peers and looking at other teams' designs	• Engaging in negative team dynamics • Focusing on competition (worrying about performing less well than other teams)
• Using the EDP to guide next steps • Referencing background information to inform next steps	• Ignoring background information that could inform next steps
• Asking for help from the teacher	• Seeking the "right answer" from the teacher
Positive Emotions / Identities	**Negative Emotions / Identities**
• Expressing a positive emotion • Not appearing to take on a failure identity	• Expressing a negative emotion / failure identity • Appearing not to care

Andrews examined how upper elementary student thinking evolved within an engineering workshop. Andrews found that challenges that were too easy and thus, resulted in few design failures, did not push students to evolve in their thinking about the underlying reasons for design success [13]. Those students whose designs initially failed and who subsequently engaged in failure analysis and improvement—akin to Crismond's four-part diagnostic troubleshooting process [9, 10]—had a more robust understanding of reasons for design success or failure. Andrews work and our own also supports the idea that design testing processes need to be followed accurately and testing results be interpretable in order to support the failure analysis and improvement process [12, 13].

Research on Failure and Diagnostic Troubleshooting in Early Childhood

There has been little research that specifically attends to design failure and student responses to design failure at the kindergarten level (ages 5-6) or in other "adjacent" early childhood grade levels (e.g., grades PreK or 1) or ages (e.g., ages 4 or 7). A study by Ehsan, Rush Leeker, Cardella, and Svarovsky examined how four girls (ages 7-11 years) with their parents engaged in diagnostic troubleshooting during an engineering design challenge [14]. In some ways, the children behaved like Crismond and Adams' informed designers (e.g., engaging in a robust failure analysis)—especially as they observed and diagnosed [7]. In other ways, the children, especially with regard to explaining and fixing, behaved more like beginners. They also did not move through the steps of observe, diagnose, explain, remedy necessarily in that order. Scaffolded support from parents encouraged more informed diagnostic troubleshooting.

Kendall utilized clinical interviews to investigate how both kindergartners (N=6) and third graders (N=9) evaluated two researcher-generated design solutions; we will focus on kindergarten results here, which were related to a bridge design challenge [15]. Three kindergarten teams were interviewed using a clinical interview, which included such questions as: "What can you tell me about these bridges? What is good about this bridge / bad about this bridge? [and, for the bridge not identified as the best of the two] How would you redesign it to make it better?" [15, p. 7]. The kindergartners were then allowed to try to redesign the bridge. Study findings included that kindergartners tended to focus on the positive aspects of the designs presented to them, had difficulty identifying and describing salient variables related to design performance, and had difficulty analyzing sources of failure. Also, in subsequent redesigns, the kindergartners tended to "start over from scratch, rather than troubleshoot" [15, p. 11]

Finally, a study by Rynearson, Moore, Tank, and Gajdzick examined evidence-based reasoning among kindergartners engaged in a STEM curriculum, identifying evidence-based reasoning at multiple points throughout the design process, including during the "Decide" step of the design process during which students considered what worked well in their design and what they would change if they were to design it again (aspects of diagnostic troubleshooting). Most of the evidence-based reasoning these researchers identified occurred as a result of teacher guidance, questioning, and prompting [16]. Rynearson and colleagues argued that it was developmentally appropriate for teachers to encourage evidence-based reasoning by asking students to explain their reasoning; a particularly useful prompting question was: "Why?"

Research Questions

We investigated three research questions for this study:

1. How do kindergartners engaged in an engineering design challenge analyze (i.e., diagnose and/or explain) their design failure experiences?
2. Do kindergartners whose designs fail choose to persist by trying again?
3. How do kindergartners whose designs fail apply testing results and failure analysis when creating their next design attempt?

Context

Participants and Schools

We recruited participants from five kindergarten classrooms across three schools within a school system in the mid-Atlantic region of the United States. Adamsville Elementary is a Title I school in an urban area with about 500 students. Blakely Elementary is in a rural area and has about 100 students. Kellerton is in a middle-class suburban area with about 400 students. (Note that all school and student names are pseudonyms.) We chose not to collect demographic data on gender, race or ethnicity. The schools and classrooms were balanced with regard to reported numbers of boys and girls, and the kindergarten classrooms were representative of the ethnic and racial make-up of the schools. Adamsville was the most diverse site with regard to race and ethnicity; the school website reported the following: 45% African American, 30% white, 14% two or more races, 10% Hispanic, and other categories too low to report. Blakely reported having 85% white students with other categories too low to report, and Kellerton reported 4% African American, 87% white, 6% two or more races, 3% Hispanic, and other categories too low to report.

We used two of four kindergarten classrooms at Adamsville, the single kindergarten classroom at Blakely, and two of three kindergarten classrooms at Kellerton. (Principals at Adamsville and Kellerton preferred that our research not be conducted in the other kindergarten classrooms in which there were early-career teachers.) The study occurred during the second half of the school year, when participants ranged in age from 5.5 to 7 years. A total of 53 kindergartners participated in the study with the following rates of participation: (1) Adamsville (36% participation; 13 participants); (2) Blakely (100%; 9); and (3) Kellerton (70%; 31).

Curriculum

Before data collection, students were engaged in two science lessons that were either co-taught by the first author and classroom teacher (Blakely and Kellerton Elementary) or taught by the first author’s elementary science teaching interns (Adamsville Elementary). The first of these lessons was about how forces (pushes) cause a change in motion [17]. The second was about inertia. In this second lesson, students learned through experimentation that wooden blocks are heavier and harder to move than foam blocks of the same dimensions [18]. Each of these first two lessons was about 30 minutes.

After this, the first author introduced the students in each classroom to a Hexbug Nano® robot named Henrietta and to the engineering design challenge involving Henrietta that was central to the study. This introduction was about 20 minutes in duration and was addressed to each whole class of students. The students observed how the toothbrush-head-sized, vibrating Henrietta moved randomly in circles and arcs on the linoleum floor, quickly moving away from where Henrietta had started her journey. The first author elicited from students what we could use so that we might contain Henrietta—keeping Henrietta from “running away”—and also allow Henrietta to have plenty of room to move: a fence. The first author showed the students a model plastic split rail fence and asked if it would work. The students unanimously replied that it would not and watched as Henrietta, placed inside a loop of this split rail fence, moved under it and away. Having established the problem, the first author then presented the goal, constraints, and criteria for the design challenge:

> Goal: To create a fence for Henrietta.
>
> Constraints: Students can use up to 10 foam blocks and 10 wooden blocks to make the fence. (Note that these blocks were investigated in the second science lesson.)
>
> Criteria: The fence should:
>
> (1) Be as big as possible to allow Henrietta to move around.
>
> (2) Contain Henrietta for at least 30 seconds.

Altogether, the science lessons and introduction to the design challenge occurred over a period of about two weeks. Data collection for the study ensued and lasted for one to two weeks. After the research was complete, all of the students in each of the kindergarten classrooms at Adamsville, Blakely, and Kellerton Elementary worked together in teams to design and re-design a fence for Henrietta; this team engagement in the challenge was not a part of the present study.

Research Design

In this study, we used interactional ethnography to explore how the study participants analyzed their first designs and, if their designs failed, to investigate how they analyzed the failure and (perhaps) attempted to remedy the failure. Our ethnographic perspective enables us to observe what participants "do, say, and make" [19, 20]. Our primary means of observing what participants did, said, and made was via semi-structured cognitive clinical interviews with individual participants, which occurred in the days following the introduction to the engineering design challenge [21, 22].

Semi-Structured Cognitive Clinical Interviews

We utilized a protocol as a guide for the interview process, but allowed the interviewer to add follow-up or contextually relevant questions as necessary [21]. Similar to the interviews in Kendall's work [15], these interviews were regarded as cognitive clinical interviews because they included a combination of each student constructing designs, narrating their design thinking, and responding to interviewer questions [22].

Interview steps and questions relevant to the present study in the protocol included the following:

1. Say: "Let's put Henrietta in your fence to see if it keeps her in."
2. Say: "We will see if she can stay inside the fence for 30 seconds. Ready?"
3. Turn Henrietta on, and place Henrietta inside of the fence. Turn on the timer and let it run for 30 seconds or until Henrietta escapes.
4. Ensure that child watches closely.
5. If fence fails (i.e., Henrietta breaks free), ask: "What happened? How did she get out?"
6. Ask: "Do you want to try to make another fence?"
7. If so, allow participant to make another fence.
8. Ask: "How will this fence work to keep Henrietta in?"

Note that the protocol provides questions and prompts reminiscent of those by teachers or parents that encouraged diagnostic troubleshooting and evidence-based reasoning in prior aforementioned studies [14, 16]. After posing the protocol questions, the first author asked participants to explain how the new fence is different/better than the first try fence.

The first author conducted all interviews, which took place in a quiet room in the school. Interviews were audio- and video-recorded. Full interviews—which extended beyond the questions relevant to the present study—lasted between 20 and 30 minutes.

Data Analysis

We created pseudonyms for each of the 53 participants. We sent audio files of the interviews to a transcription service, and then checked each transcript against the video to make any necessary corrections and add gestures and participant actions to the transcript. Interview questions on the protocol provided a starting point for codes. As we iteratively read transcripts, revisited video footage, identified relevant interview excerpts, and applied organizational codes, we also allowed for substantive codes to emerge [21, 23].

We began the coding process by randomly selecting about one third of the 53 interviews for each of us (first and second author) to code independently. After comparing our coding of this first set, we adjusted our coding scheme and clarified code descriptions in our code book. Once we reached consensus on the first set of interviews, we divided the remainder of the interviews in half, creating two more sets. Each of us independently coded one of these sets. Following that, we each reviewed the coding that the other had done and discussed and resolved any discrepancies.

We used Excel to organize the codes, sub-codes, and evidence to support those codes for all participants. This enabled us to better observe patterns in our data and also to calculate percentages (e.g., the percentage of participants whose design failed). These percentages are meant to help us describe our particular sample and we do not mean to generalize beyond this to, for example, reflect percentages of all kindergartners.

Researcher Roles

As mentioned above, both authors contributed to data analysis. While the second author's role was purely that of a researcher in this project, never having met the participants in person, the first author had an "active membership" role in the classroom community [21, 24]. Prior to the interview, the first author spent about six hours in each classroom or with students. Activities included:

- teaching the lessons leading up to the interviews;
- volunteering and/or observing in each classroom; and
- engaging with each participant in a spatial reasoning clinical interview (as part of another part of the project).

By the time that the participants participated in the interview relevant to the present study, they were quite familiar with the first author.

Findings

In this section, we present four categories of findings. First, we share how many first try fences failed during testing with Henrietta, the Hexbug Nano® robot. Second, we explore how they failed according to our own observations of the testing process—what we call the "researcher failure analysis." Third, we compare this researcher failure analysis to how the participants diagnosed and explained their fence failure—"participant failure analysis." Finally, we examine the extent to which second try fences incorporated improvements that responded to the researcher failure analysis.

First Try Fence Failure

Based upon our analysis of participants' first try fences, 42 of 53 (79%) failed because Henrietta escaped in 30 or fewer seconds. The average time to failure was 11 seconds (standard deviation = 9 seconds). Nine fences (17%) successfully contained Henrietta for more than 30 seconds. Note that we identified fence failure (or success) based upon the containment criterion only. The other criterion was to have as much space as possible for Henrietta to move around. This was more of a subjective criterion that was important but did not dictate failure or success as we describe here.

Two first try fences (4%) were not tested. Those were created by Tyler and Gavin, respectively. Tyler had created a first try fence out of all 10 foam and all 10 wooden blocks. When asked if he was ready to test his fence, he knocked it over and said that he wanted to "add something." When asked why, he responded: "Cause she could get out with these [holding up two foam blocks.]" Gavin had a similar experience. He created and described his first try fence, which used all 10 foam and all 10 wooden blocks but had one large gap. The following transpired when Gavin was asked about how this first try fence would work:

Interviewer:	So, tell me how your fence will work to keep her from getting away.
Gavin:	Mm, it could just bump if, if it did like, if we have more blocks … it could like, it could like go all around [gesturing to the other sides of the board], but this makes me have to … so – [Gavin begins to disassemble the left edge of his wall.]
Interviewer:	Are you going to build it differently now?
Gavin:	Yeah.

This transpired before Gavin had a chance to test his fence. One interpretation of Gavin's and Tyler's first try experiences is that they mentally tested their first try fence and determined that it was not going to be successful; they did not appear to see a need to conduct a real physical test in order to know that they needed to try again.

Researcher Failure Analysis: Reasons for Design Failure

Based on our own failure analysis, each fence that failed did so because of one or two of the following reasons:

Reason 1. Henrietta pushed **foam blocks** out of the way and escaped (79% of 42 participants whose designs were tested and failed).

Reason 2. Henrietta escaped through a **gap** in the fence (17%).

Reason 3. Henrietta pushed against a **wooden block corner** until the blocks moved and she escaped (12%).

Reason 4. The fence **did not encompass an area**; there was a large portion of missing fence through which Henrietta could escape (7%).

Figures 1-5 show fences that failed due to these reasons.

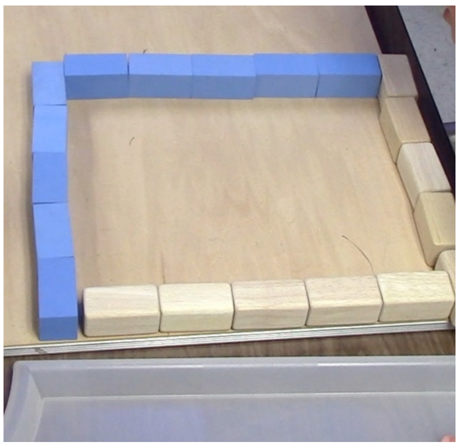


Figure 1. Charles's first try fence failed due to Reason 1 (Henrietta pushed through foam blocks).

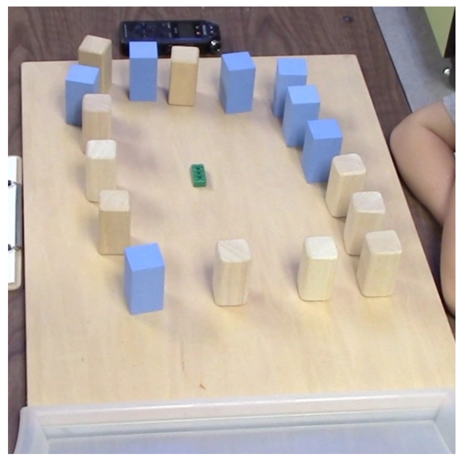


Figure 2. Andrew's first try fence failed due to Reason 2 (Henrietta went through a gap).

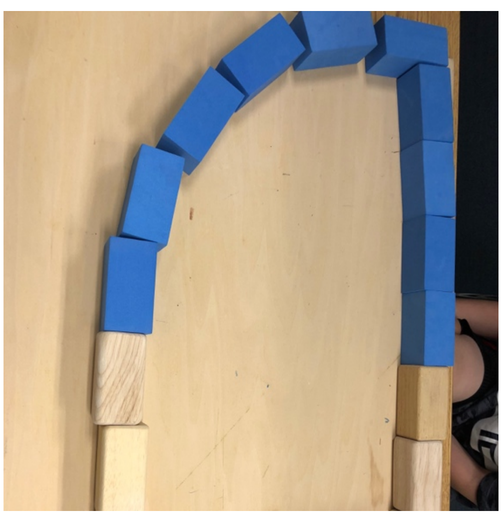


Figure 3. Caleb's first try fence failed due to Reasons 1 and 2 (Henrietta pushed through a gap between foam blocks); full fence not shown.

Figure 4. Ava's first try fence failed due to Reason 3 (Henrietta pushed where two wooden block corners touched).

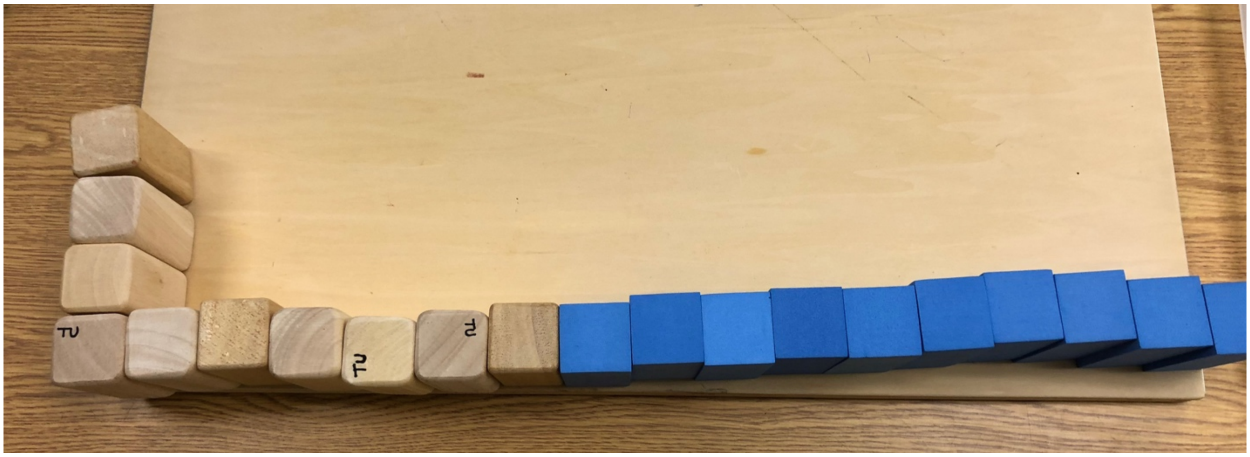


Figure 5. Austin's first try fence failed due to Reason 4 (does not encompass an area).

Note that in Figure 2, not only did Andrew have large gaps in his fence, he also used foam blocks that Henrietta could push. However, the evidence from the testing process for Andrew to observe was that Henrietta moved through the gap; Henrietta did not push one of his foam blocks because Henrietta did not happen to run into a foam block.

Failure Analysis by Participants

We evaluated the correctness of the failure analysis of the 42 participants whose designs failed as compared to our researcher failure analysis. Overall, 69% provided a correct diagnosis of the reason for failure; 21% provided a partially correct diagnosis, 7% had an unclear response, and 2% had an entirely incorrect diagnosis. As we will discuss in the sections that follow, some extended these diagnoses to include explanations. The sections that follow address correctness of participants' failure analysis according to the following research failure analysis categories: (1) Reason 1 Foam Blocks, (2) Reason 2 Gaps, (3) Reason 1 Foam Blocks and Reason 2 Gaps, (4) Reason 3 Wooden Block Corners, and (5) Reason 4 Did Not Encompass an Area.

Reason 1 Foam Blocks

Of those 27 participants whose fences failed because Henrietta was able to push a foam block out of the way and escape (Reason 1), all but two (93%) correctly identified this reason for failure. For example, when asked what happened, Matthew pointed to a corner where Henrietta escaped. The interviewer responded: "She went there. What was she able to push?" Matthew replied: "This [picks up corner blue block.] The blue block." Here, Matthew has accurately diagnosed the reason for his design failure: Henrietta pushed the blue foam block (note that all foam blocks are blue).

Some participants (12; 44%) went further, adding an explanation to their diagnosis. This explanation arose from prior knowledge that they learned in the second science investigation (i.e., that wooden blocks are heavier and easier to move than lighter foam blocks). For example, Madison shared: "… 'cause these [pointing to foam blocks] are light, she went out … cause she could push it." Of this group of explainers, some did not always use accurate language in their explanations. For example, Brooklyn explained that the foam blocks that Henrietta pushed "don't have weight." Kaylee explained that Henrietta escaped through the blue blocks "because the foam blocks are even fluffier, these ones [touching the foam blocks] are even softer to get out. These ones [touching the wooden blocks] are harder to get out."

Two participants whose fences failed because of Reason 1 did not provide a fully correct diagnosis. Charles's response was partially correct. He identified the correct corner where Henrietta had escaped but focused on the wooden block (which had not moved) rather than the foam block (which had moved). Arianna's response was incorrect. She offered: "It's knocked over … because Henrietta go this way." However, the block was pushed, not knocked over.

Reason 2 Gaps

There was only one fence, belonging to Andrew, that failed because Henrietta escaped through a gap (Figure 2). When asked, "Why did she get out?," Andrew correctly responded: "'Cuz there's a hole." Although not a detailed response, Andrew correctly diagnosed the reason for Henrietta's escape.

*Reason 1 Foam Blocks **and** Reason 2 Gaps*

Six fences that failed (14% of 42) involved failures that were related to both the use of foam blocks and the presence of gaps. This was challenging for the participants to diagnose, with five of the six participants (83%) identifying one or the other reason, but not both—two of which provided explanations with their diagnoses—and another (Emily's) being incorrect altogether. An example of the former of these cases is when Caleb (Figure 3) explained that Henrietta escaped "by knocking one of the blocks out." Caleb identified this block as being a foam block that was knocked out "because it's more soft and not hardened." Caleb, Brandon, Natalie, and Sarah ignored the gap as a contributing factor with regard to failure. Another participant, Mia, ignored the contribution of the ease of pushing a foam block in favor of simply explaining: "It went through crack."

Emily actually ran two tests of her first try fence. In the first test, Henrietta pushed a foam block at a point in the fence where a wooden and foam block touched. In the second test, Henrietta escaped through a gap. Emily identified neither of these reasons when asked, "Why did Henrietta get out?" Emily responded: "Um, cause there was too much blocks." The interviewer followed by restating, "Too much blocks? And that's why she got out?" Emily nodded yes.

We wonder if there was too much information to process—too many reasons for failure for Caleb, Brandon, Natalie, Sarah, and Mia and too many tests for Emily—for these six participants to make a complete diagnosis of their fence failures. An additional complexity for Natalie was that she had a two-walled fence that failed due to a gap in her inner fence followed by a foam block in the outer fence area.

Reason 3 Wooden Block Corners

Another challenging diagnosis to make was when Henrietta was able to push between two wooden blocks. This occurred in locations where only the corner edges of wooden blocks touched or in fence corners. Five participants (12%) experienced this kind of design failure: Ava (Figure 4), Grace, Wyatt, Isabella, and Jonah. Unlike the prior science investigation comparing wooden and foam blocks—there was no prior experiment to prepare participants to consider trouble with corners, even those made by wooden blocks. These five participants, in particular, witnessed that Henrietta, if "stuck" in one wooden block corner or intersection could persistently push hard enough to move those "heavy" wooden blocks. The reasons for these design failures have to do, in part, with the amount of surface area providing friction to resist Henrietta's pushing. This is clearly beyond the scope of basic principles of force and inertia that participants learned in recent science lessons.

It is difficult, then, to determine what correct failure analysis looks like for this wooden block corner failure. Wyatt, Isabella, and Jonah offered different and accurate diagnoses: pointing to the corner where Henrietta escaped (Wyatt); "[Henrietta] kinda made a hole right here" (Isabella); and "She like got in a crack" [uses finger to demonstrate how Henrietta pushed between two wooden blocks] (Jonah).

Ava was less specific, saying "she moved it" and then offering "I think it's [the fence is] not big enough." Although she seemed to identify that the fence blocks moved, she incorrectly associates the problem having to do with the fence size. Grace skipped the diagnosis and jumped to an evaluation: "It must not have been in tightly." This reason is somewhat close, but as we mentioned previously, the reasoning is complex here. Ultimately, we identified Ava's and Grace's failure analyses as each being partially correct.

Reason 4 Not a Fence

Three participants created a fence that did not encompass an area. Ideally, failure analysis would entail the participants identifying that Henrietta escaped because there was no fence all around her. We identified Austin's response as being partially correct. He offered that he "could use more blocks," pointing to the area where fence would be if he had more blocks and indicating that he would put blocks all around the edge of the board (Figure 5). This implicitly acknowledges the existence of the missing part of the fence; however, it does not do so explicitly and it does not acknowledge the constraints of using no more than 10 wooden and 10 foam blocks.

Marshall and Joy's failure analyses were unclear. Marshall responded that he would: "Make it more bigger." We are unsure what it is that needs to be "more bigger" here. Joy did not analyze her fence/wall, instead saying "I wanna leave it."

For each of these cases, we suspect that the intent of the challenge to make a fence that would encompass Henrietta was not well understood. As we will address in the next section, Joy and Austin chose not to try again. Marshall, however, seemed to gain an understanding of the challenge for his second try fence.

Choosing to Persist

When given the opportunity to create a second fence, 39 of the 42 participants whose first designs failed (93%) opted to try again. Of those three (7%) who opted not to create a second fence, two showed evidence of frustration with the challenge (Austin and Mason) and one, Joy, suggested that s/he was satisfied with the first try fence despite its failure in the test.

Further, Gavin and Tyler, who never tested their first try fences, decided to recreate their fences for a second try, albeit one that was not based upon testing results. Another measure of persistence was that of the nine participants whose first designs were successful, eight (89%) enhanced their fence by reinforcing it to ensure that Henrietta would not escape.

Relationship between Second Try Fences and Researcher Failure Analysis

In this section, we explore the relationship between students' second try fences and the researcher failure analysis. The question here is: Did students apply testing results correctly and completely to inform their second designs? In our numerical analysis to address this question, we have included 34 of the 42 participants' whose first try fences failed.

As mentioned in the previous section, three of the 42 participants chose not to create a second try fence; thus, they are excluded from this analysis. Also, five of the 42 participants' designs failed because of Reason 3 for which Henrietta was able to push through wooden blocks that met at a corner. We have excluded these five participants from our numerical analysis because making changes to the fence designs in response to this particular design failure was beyond the intended focus of this design challenge for this age group; this focus was intended to be about inertia and the prevention of gaps. Potential changes to address the wooden corner issue could include making a smoother inside part of the fence to prevent Henrietta from "digging" into joint made by a corner and/or reinforcing corners or other weak points with additional blocks. The five participants' second designs were altered by: adding more blocks [most of which touched along surfaces rather than edges] (Ava); making the blocks "tighter" (Grace); reinforcing the wooden fence with foam blocks (Wyatt); reducing gaps [but also adds foam blocks] (Isabella); and making a square fence instead of a circle (Jonah).

Thus, the 34 participants included in our analysis here are those whose first try fences failed for Reasons 1, 2, or 4 and those who created a second try fence. Of these, 38% of second try fences completely responded to the researcher failure analysis, specifically addressing one or both reasons for failure. Nearly half (47%) partially responded to the researcher failure analysis, and 15% did not make changes that were related to the researcher failure analysis. As a matter of comparison, Table 2 shares this information in the second major column and compares it to the first major column that summarizes the participant failure analysis correctness of the same group of participants. What is interesting to note here is that a greater percentage of participants had a fully correct participant failure analysis (74%) as compared to the percentage of participants who completely responded to the researcher failure analysis (38%) within their second try fence.

Table 2. Participant failure analysis and second try fence design as compared to researcher failure analysis (N=34 participants)*

Participant Failure Analysis as compared to Researcher Failure Analysis (RFA)		Response of Second Try Fence Design to RFA	
Comparison to RFA	Percentage (Number)	Response to RFA	Percentage (Number)
Correct as compared to RFA	74% (25)	Completely responded to RFA	38% (13)
Partially correct as compared to RFA	18% (6)	Partially responded to RFA	47% (16)
Incorrect as compared to RFA	6% (2)	Did not respond to RFA	15% (5)
Unclear	3% (1)		

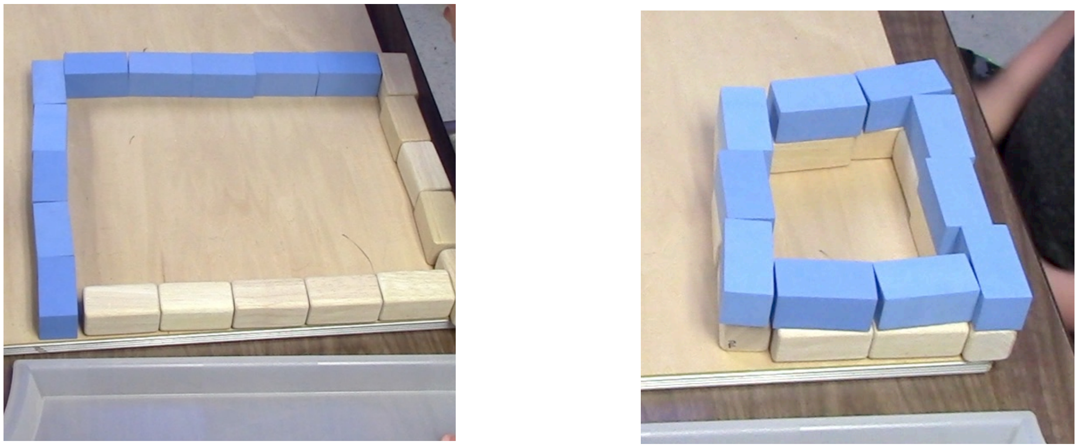
* N=34 includes participants whose first try designs failed due to Reasons 1 and/or 2 or Reason 4 and those who created a second try design

We will share three examples from the 34 participants in each of the following categories in which participants: (1) completely responded to researcher failure analysis, (2) partially responded to researcher failure analysis, or (3) did not respond to researcher failure analysis.

Completely Responded to Researcher Failure Analysis

Of the thirteen participants in this category, 11 (85%) both had a correct participant failure analysis and completely responded to the researcher failure analysis. In other words, they both identified the reason that Henrietta escaped in their first try fences and "fixed" this problem in their second try fences. One participant who completely responded to the researcher failure analysis in his second try fence was Marshall, whose failure analysis of his first design was unclear ("make it more bigger"). His first try fence did not encompass an area, but his second try fence did.

Another participant in this category was Charles, whose first design was shown in Figure 1 and again here on the left side of Figure 6. His failure analysis was partially correct; he identified where Henrietta had escaped, but incorrectly stated that the wooden block (not the foam block) was to blame. His second try fence is shown in Figure 6. Note that he created his fence with an exclusively wooden base with foam reinforcement on top. Thus, Charles completely responded to our researcher failure analysis, even though his own failure analysis was only partially correct.



First try fence　　　　Second try fence

Figure 6. Charles's first and second try fences.

Partially Responded to Researcher Failure Analysis

There were sixteen participants in this category who applied the researcher failure analysis ideas in part. This included three types of partial response cases:

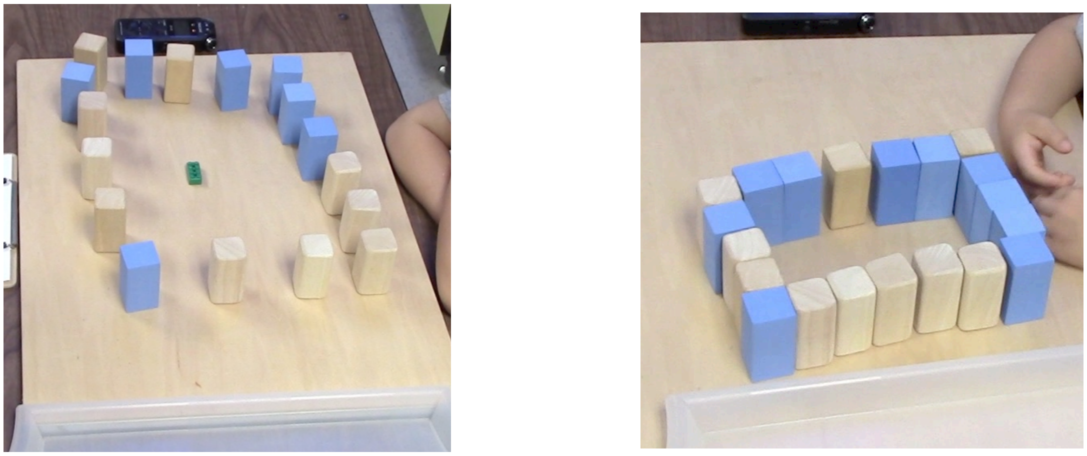
Partial Response Case 1. Participants whose first try fence failed due to Reason 1 (use foam blocks), and they used fewer foam blocks (but not zero foam blocks) to create fence walls.

Partial Response Case 2. Participants whose first try fence failed due to Reason 2 (gaps), and they fixed most but not all of the gaps in their fences.

Partial Response Case 3. Participants whose first try fence failed due to Reasons 1 and 2, and they only addressed one of these problems and not the other.

Five of the six participants who had two failure reasons (Reason 1 and 2) were in the situation described by Case 3. The sixth was in the category of participants who did not respond at all to researcher failure analysis.

One participant who partially responded to our researcher failure analysis in his second try attempt was Andrew. An example of Case 2, above, he needed to fix the gaps in his fence (see Figure 2), which he identified in his own failure analysis. He fixed many but not all of those, as is evident in a comparison of his first and second try fences in Figure 7.



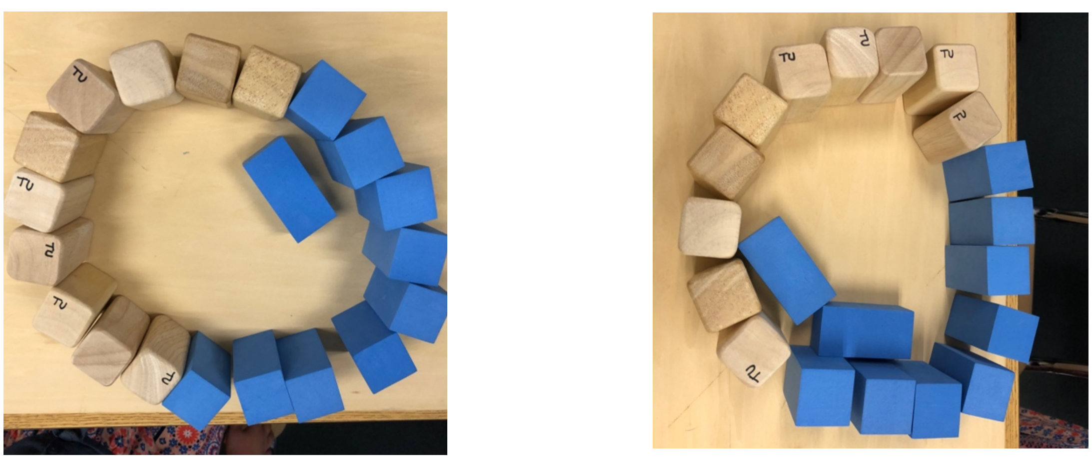
First try fence

Second try fence

Figure 7. Andrew’s first and second try fences.

Did not Respond to Researcher Failure Analysis

In total, four of the five students whose second try fences did not respond to researcher failure analysis at all had a correct participant failure analysis. This was the case for Kaylee (Figure 8). Despite Kaylee’s correct diagnosis and explanation of why her first try fence failed—Henrietta pushed through the foam blocks, which are “softer” to get out; the wooden blocks are “harder” to get out—her second try fence still contained foam blocks. In contrast to the other participants in this category, Emily neither had a correct failure analysis nor was able to apply researcher failure analysis to her second try fence.



First try fence

Second try fence

Figure 8. Kaylee’s first and second try fences.

Conclusions and Discussion

In this study, we have aimed to investigate how students persist and learn from failure, an epistemic practice of engineering [4]. Specifically, we wanted to know how students engaged in failure analysis—responding to a very simple but loaded question, "What happened?"; whether they persisted in the design process, choosing to try again or not; and, for those who tried again, to what extent their second tries responded to "what happened" when the design failed.

Failure Analysis by Participants

Overall, most of the participants (70%) whose designs failed were able to accurately diagnose the failure. Some (19%) were able to partially identify design failures. We address two themes within this section to unpack these findings further: (1) that complex failures are harder for the kindergartners in our study to diagnose; and (2) that there may be multiple layers of explanations to consider.

Complex Failures are Harder to Diagnose

One of our broad findings is that the more multifaceted the design failure, the more challenging it was for the participants to diagnose. For example, most of the participants who only partially identified design failures either had a fence that failed due to a combination of the use of foam blocks and gaps (Reasons 1 and 2) or experienced design failure due to wooden block corners (Reason 3).

Most of the failure analysis was focused on Reason 1 (use of foam blocks), which was an intended focus for this design challenge that built upon a scientific investigation of inertia. We also anticipated that gaps in the fence could be failure points and suspected the idea of Henrietta being able to move through a gap (like an open door) was accessible to kindergartners (Reason 2). While we have evidence to support the idea that participants like Andrew could identify and address gaps, there were other examples in which gaps went unnoticed. Also based on prior work to develop the design challenge, we suspected that some students would create long walls rather than area-encompassing fences (Reason 4). This is why we introduced the challenge by showing an encompassing split rail fence that went around Henrietta (but included gaps through which Henrietta could escape).

Finally, in our design challenge development process, we observed occasional instances in which Henrietta would push her way out of a wooden corner (Reason 3). These seemed relatively rare and unavoidable and we decided not to preemptively address these issues due to their complexity. The first try fence failure analyses for those students who grappled with Reason 3 confirmed that this was a challenging way that the fences could fail. The complex nature of this failure was also evident in the creation of their second try fences. This is reminiscent of the findings from Andrews' and our own study that testing processes should be as interpretable as possible [12, 13]. We wonder if using larger wooden blocks that Henrietta could not push as easily may help to solve this problem. The blocks that we used were chosen for their ubiquity in kindergarten block centers and for their identical dimensions to foam blocks that we could easily purchase.

Prompting Explanations and Multiple Layers of Explanations

We also noticed in students' discussions of their first try fence design failures that while most diagnosed the reason for failure, fewer provided an explanation beyond saying that it was because of the blue/foam block or the hole, for example. This is consistent with aforementioned findings from Ehsan and colleagues [14]. Diagnosis and explanation are two facets—after observation—of diagnostic troubleshooting [7, 9, 10]. The reason for a lower frequency of explanation is due, in part, to interviewer error in which not all "What happened?" questions were followed by "Why did this happen?" As articulated by multiple studies, such questions and prompts are important scaffolds for student engagement in practices such as diagnostic troubleshooting or supporting claims with evidence-based reasoning [14, 16]. However, it is worth considering what counts as a robust explanation at the kindergarten level here. We wonder: Is the identification of not only where Henrietta escaped a good enough diagnosis, and then the identification of a blue foam block as the culprit an explanation—albeit a surface-level one—beyond that? In our work thus far, we did not count a blue block identification as an explanation; rather, explanations in our analysis included something about the foam blocks being easier to move or lighter (or fluffier!) and the wooden blocks being harder to move, etc. We see layers of explanation here and wonder to what extent we should push for such explanations in our clinical interviews.

Persisting

Perhaps due to the supportive environment of the clinical interview with a familiar volunteer/teacher (first author) or guided by an intrinsic interest, most of the students opted to try again. Only four of 53 participants, three whose first try failed and one whose first try succeeded, chose not to try again. We sensed frustration by two participants, and in both cases, these students desperately wanted more blocks, which they could not have; they focused on their need for more blocks rather than deciding to reduce the size of their fence. Thus, reflecting back on Table 1, only two participants out of 53 engaged in what we would identify as a negative emotion. That said, there were no tears or tantrums. Although not a focus of the present study, there were many smiles among many participants.

Using Testing Results to Improve

Most of the participants applied testing results (as per researcher failure analysis) to their second try fences either completely (38% of 34 participants who created a second design and whose first design failed due to Reason 1, 2, or 4) or partially (47%). As we addressed in the findings section, there was a difference between those who correctly engaged in failure analysis (74%) and those who completely applied this failure analysis to their second design (38%). We have a theory-practice gap here in which many students knew what they needed to remedy in their first try designs but did not or could not implement this remediation in their second designs. A very significant reason for this, which we explore in depth in another paper, is that many participants had challenges with the tradeoffs between the fence perimeter size and the use of the foam blocks, which most of the participants knew Henrietta could push through. Before and/or after first try fence testing, participants knew that foam blocks were easy to push and would not make for good fence walls but opted to use them anyway when they did not have enough wooden blocks to create a fence of a certain desired size. This tradeoff between two criteria was a challenge for the kindergarten participants in this study.

An overarching theme from our study is that the kindergartners in our study could engage in failure analysis, could persist, and could apply testing results and failure analysis in their next design attempts. The participants ranged from being informed designers who engaged in diagnostic troubleshooting—observing, diagnosing, explaining and remedying like professional engineers, albeit for an age-appropriate design challenge—to beginners whose failure analyses and improvement ideas were not as closely connected to testing results [7, 9, 10]. They did so in the very scaffolded environment of the cognitive clinical interview. It also speaks to the ways in which the complexities of the design challenge—including multiple ways of failing and multiple criteria—that can make failure analysis and subsequent improvement difficult for young learners.

Limitations

We have attempted to make this study as valid as possible through the use of an interview protocol; our close examination of video for what participants did, made, and said; our use of intercoder agreement to arrive at final coded excerpts; and the first author's involvement in each of the classrooms. One threat to validity is that the first author, in particular, knowing the students and teachers, may have more positively interpreted participants' responses. A balance to this potential bias is the second author's researcher role and stance. We may have also interpreted students' language and behaviors differently than they intended; however, we attempted to address this through our intercoder agreement process.

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