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RESEARCH REPORT

Failure and Improvement in Elementary Engineering

Matthew M. Johnson[a1], Gregory J. Kelly[a], Christine M. Cunningham[a]
[a]*Penn State University, USA*

Abstract: *Recent science education reform documents in the United States have called for teachers to teach content related to engineering and science and to do so by engaging students in disciplinary practices. One important practice of engineering is improving from failure. Thus, students should experience productive failure as part of engineering design activities. However, engineering is a new subject for most elementary teachers. Historically failure has had negative connotations in elementary and precollege classrooms. To scaffold students through failure as they learn from and improve engineering designs, teachers will need to understand failure and pedagogical strategies for managing it. This study uses discourse analysis of video from eight elementary classes engaged in engineering to examine the nature of failure in engineering design projects. It also investigates how the collective actions of students and teachers support or constrain the process of improvement from engineering design failure. From these data, we propose a model of improvement through failure. This includes a classification of types and causes failure as well as facilitating conditions that must be present for improvement. We explore three features of engineering and three features of classroom cultures that contribute to learning to engage in productive failure.*

Keywords: *engineering education, failure, elementary*

[1] Matthew M. Johnson, Ph.D.: Center for Science and the Schools, Penn State University, 182 Chambers Building, University Park, PA 16802. Email: mjohnson@psu.edu

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Introduction

Engaging students in engineering in precollege settings has the potential to improve learning in science and math, develop a better understanding of the human-made world, increase students' understanding of and their ability to engage in engineering design, foster problem-solving abilities and dispositions, and foster understanding of the interconnections between science, engineering, and technology (Cunningham & Sneider, in review; Katehi, Pearson & Feder, 2009; National Research Council [NRC], 2012). Engineering is appropriate even with young children-they naturally engineer as they tinker and interact with the natural and human-made world (Cunningham, 2018; Cunningham & Carlsen, 2014a; Petroski, 2003). In the last decade, engineering has gained traction as part of science education; in the United States the Next Generation Science Standards (NGSS) (NGSS Lead States, 2013) included engineering core ideas and practices. The framers of NGSS explicitly named eight practices of scientists and engineers. These practices stemmed largely from science (Cunningham & Carlsen, 2014a) and only two of these practices evidenced differences between the domains of science and engineering (NRC, 2012).

The Framework for K-12 Science Education (NRC, 2012) and NGSS (NRC, 2013) promote "three-dimensional" learning through engaging students with disciplinary core ideas, science and engineering practices and crosscutting concepts. However, while disciplinary core ideas in physical sciences refer to ideas through statements like, "Pushes and pulls can have different strengths and directions," (PS2.A; NGSS, 2013), engineering core ideas are described in ways that refer to practices. Consider these two examples: "Defining engineering problems" (ETS1.A) and "Optimizing the design solution" (ETS1.C) - they each make reference to engaging in organized activity, rather than referring to specific engineering ideas. Engineering takes even less prominence in the Framework because engineering is portrayed as only an application of science, rather than a discipline in its own right, with specific practices and disciplinary core ideas (Cunningham & Carlsen, 2014b).

Cunningham & Carlsen (2014a) advocated better understanding how the practices were manifest different in science and engineering. A review of studies about engineering led Cunningham & Kelly (2017) to propose sixteen epistemic practices of engineering that are used to propose, communicate, assess, and legitimize knowledge (Kelly & Licona, 2018). One important epistemic practice is persisting and learning from failure (Cunningham & Kelly, 2017; Madhavan, 2015; Petroski, 2018). Failure is a normative feature in the process of engineering (Cunningham & Carlsen, 2014a). Failure is a key feature of case studies of engineering coursework (Petroski, 1985), is used as a measure of dependability (e.g., Mean Time Between Failure) (Prasad, 1996), as a way to standardize materials and processes (e.g., "eight pound test" fishing line) (Yarnold & Brofft, 2013), as a way to verify the composition of materials (e.g., through destructive testing of concrete) (Mynarcik, 2014), and as a tool to iterate and improve future designs (e.g., "frequent fast failure") (Matson, 1996). Some engineering journals analyze failures and their causes to help others avoid similar problems and to improve future designs. These are all productive functions of failure. Failure is not a goal of engineering, or even engineering education, but failure can be used for productive learning (Kolodner, 2002).

However, failure is a term that carries rhetorical baggage in precollege education. Teachers are often hesitant to use words related to failure in their classes and negative connotations of failure in educational settings are an impediment in understanding failure in engineering design (Lottero-Perdue 2017a & 2017b). Cajas (2000) suggested that students do not naturally address the cause of failure in school projects, and few studies exist about how students plan, test, and explain their failed designs. Feedback is considered an important aspect of supporting students' improvement during engineering projects (Kolodner, 2006), and students benefit from access to expert cases and the opportunity to try again. Explicit instruction related to iteration and failure and opportunities to engage in the "failing forward" helps students design successful solutions (Marks & Chase, 2019). Cunningham & Carlsen (2014a) suggests engineering is unique because the feedback from designs failing reduce the need for a "more knowledgeable other" (Mariage, Englert, & Garmen, 2011), as is often required in science investigations. Children may not be able to evaluate a proposed explanation, but they can easily recognize when a design does not function as expected, for example, when a card tower or a model bridge collapses.

The productive use of failure in precollege engineering is an important practice that should be promoted and supported (Stretch and Roehrig, 2021; Lottero-Perdue, 2020; Cunningham & Kelly, 2017). To date there are few studies about how and why students' designs fail and how students and teachers react to these failures (Jackson et al, 2021). Of those 35 identified by Jackson and colleagues, only seven were focused on failure in engineering, and only three were focused on elementary classes (Lottero-Perdue, 2015, 2017a; 2017b). To create educational resources, instructional strategies, and professional learning that support student through productive failure, we need to better understand how students and teachers interact with failure during engineering design. This research study investigates the following research questions:

1. What is the nature of failure in elementary engineering design projects? How and why does failure happen?
2. How do the collective actions of students and teacher support or constrain the process of improvement from engineering design failure?

Such research can shed light on how failure can be used for productive educational experiences.

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Method

Theoretical & Methodological Framework

Our study is rooted in a sociocultural approach. It is informed by the empirical study of engineering practice across settings (i.e., "engineering studies"), and it considers the materials used in the engineering design process to be contributors to the interactions that should be considered. Engineering studies help us think about engineering practices. Knowledge-building (epistemic) practices are socially constructed, situated in on-going concerted activity, rely on prior discourse or artifacts, and are consequential for what counts as knowledge (Kelly & Licona, 2018). Learning from failure is one such epistemic practice in engineering (Cunningham & Kelly, 2017). We can study these practices *in situ*, looking closely at the ways people doing engineering interact to accomplish their goals (Johri, 2011).

Consistent with our overall sociocultural approach to the study of engineering education is sociomaterialism. Sociomaterialism views the social components and the artifacts used as equally important to consider (Styhre et al., 2012). In engineering work, the people and the materials are inseparable and should be studied in this way (Orlikowski, & Scott, 2008). Styhre and his colleagues (2012) assert that engineering accomplishment always derives from the capacity to identify and overcome failure, and relies on the *feedback,* which is intentionally derived, and *backtalk* from the artifacts, which can be unexpected (Yanow & Tsoukas, 2009). Our analyses focus both on the students' and teachers' interactions with each other and with the materials they utilize.

Our theoretical framework guided the research questions, methods, and analytic decisions. Because classroom engineering projects are usually completed in small groups of students and involve collective thinking, negotiating, and problem solving that rely heavily on language, we chose to take an ethnographic perspective of classroom activity that is informed by discourse analysis (Kelly & Green, 2019, Bloome, et al., 2005). An ethnographic perspective examines the ways that cultural practices (norms and expectation, rights and obligations, roles and relationships) are constructed by participants through interaction within a group (Green & Bloome, 2004). Investigations of classroom discourse requires knowledge beyond only what is available in the moments of interaction for the analyst to recognize and interpret patterns of activity (Kelly & Green, 2019). Thus, these studies typically begin with a period of ethnographic research that tries to understand the local classroom culture and norms (Gumperz, 2001). This allows the analyst to situate the activity within the classroom culture and zoom in and out between the whole experience and the parts that make it up (Kelly, 2014). An ethnographic approach allows the analyst to make selection decisions and theoretically sample from large

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video records (Kelly & Green, 2019; Kelly & Chen, 1999; Gee & Green, 1998). A more detailed description of our research approach and methodology can be found in Johnson (2019).

Data

Data for this study were derived from video records collected from 3rd – 5th grades classroom in the Northeast and Mid-Atlantic states during implementation of elementary engineering curricular units (Cunningham et al., 2020). Classrooms for our analysis were theoretically sampled (Patton, 1990) from a corpus of over 3,000 hours of video records. We selected eight elementary classrooms engaged in a civil engineering unit that asked children to design structures capable of holding weight because the failure of the bridges was easy to identify. Half of our classrooms (Cohort A) implemented a curriculum that used an engineering design process that explicitly included an opportunity to improve and that clearly articulated multiple criteria and constraints that were assessed with fair tests. The other half (Cohort B) implemented a curriculum that lacked features thought to be important in engineering design projects, including the opportunity to redesign, more than one criterion, and specified testing protocols. Data from all classrooms were used to answer Research Question 1. Only Cohort A classes were used to investigate Research Question 2 because Cohort B did not have an opportunity to improve their designs. All teachers participated in 30 hours of professional development to develop a shared understanding of engineering and technology and to become familiar with their respective curricula. None of the teachers had previously taught engineering.

Our method follows a rich tradition of discourse analysts in educational settings (e.g., Green (2012); Gee (2010); Wortham (2020); Kelly & Green (2019)) but is applied to elementary classes engaged in engineering projects. Detailed, descriptive discourse analysis captures the richness in the students and teachers' experiences with failure in ways that other methods cannot (Watkins, Spencer, & Hammer, 2014). In each classroom, one video camera was fixed on the whole class to capture movement of the teacher and whole-group activities. Two other cameras were fixed on individual student groups, with tabletop microphones on students' desks. There were approximately 6 hours of video records for each of the 8 classrooms in the study. With the three camera angles, the body of video data totalled 139 hours. We used interactional sociolinguistics (Gumperz, 2001) as a method to interpret discourse events, both verbal and non-verbal. First, we developed event maps (time-stamped, descriptive records) (Kelly & Chen, 1999) that included lesson phases and sequences to record and organize how class time was spent. Event map spreadsheets were constructed with each row representing one minute, to enable comparisons between time spent on phases and sequences. In total, 86 event maps were created to organize the 139 hours of video. These event maps allowed us identify patterns across events and to zoom in to specific classroom activities for detailed discourse analysis across the eight classrooms. In this study, we targeted instances of failed designs. After identifying these

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segments, interactions surrounding failure events were transcribed word-by-word for microanalysis but were situated within the larger context of antecedents and consequences. We used a constant comparative approach (Strauss & Corbin, 1990) for coding for failure types, failure causes, obstacles for improvement, and teacher reactions. Comparisons were made within and between groups. To increase trustworthiness, we maintained an audit trail and collaborated with and received peer review from a classroom discourse research group at our university (Creswell & Miller, 2000). See Figure 1. The authors acknowledge that they have strictly followed the applicable ethical guidelines regarding research that involve human subjects.

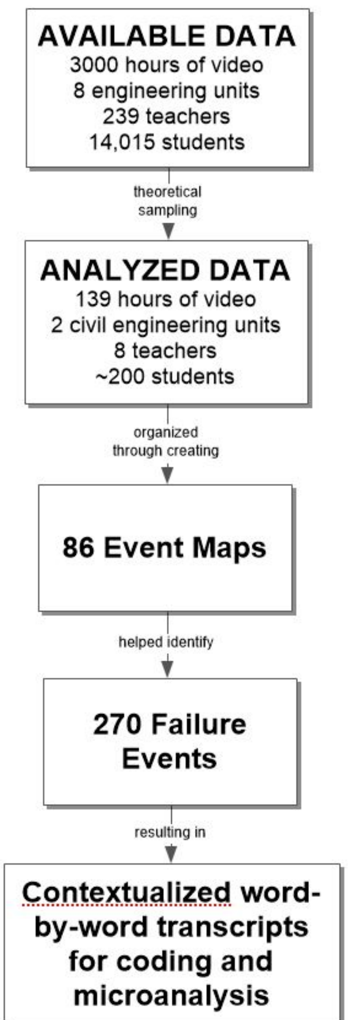

Figure 1. A schematic *summarizing* our approach with the available data

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Results

Through analysis of the patterns of events across the instances of failure, combined with discourse analysis of the antecedent activity, instances of recognition of failure, and subsequent response to failure, we identified types of failure in the engineering challenge and obstacles to improvement. Based on this analysis, we designed a model for failure and improvement that identifies ways that failure in engineering design can lead to productive learning opportunities.

Types of Failure

Not all engineering failures are alike. The differences in types of failure affect the types of reactions and discourse events that surround them. Through review of published studies of engineering work and iterative analysis and discussion of 270 instances of failure in classroom video, a system to categorize failures along three continua—stakes, intent, and referent—emerged (see Figure 2).

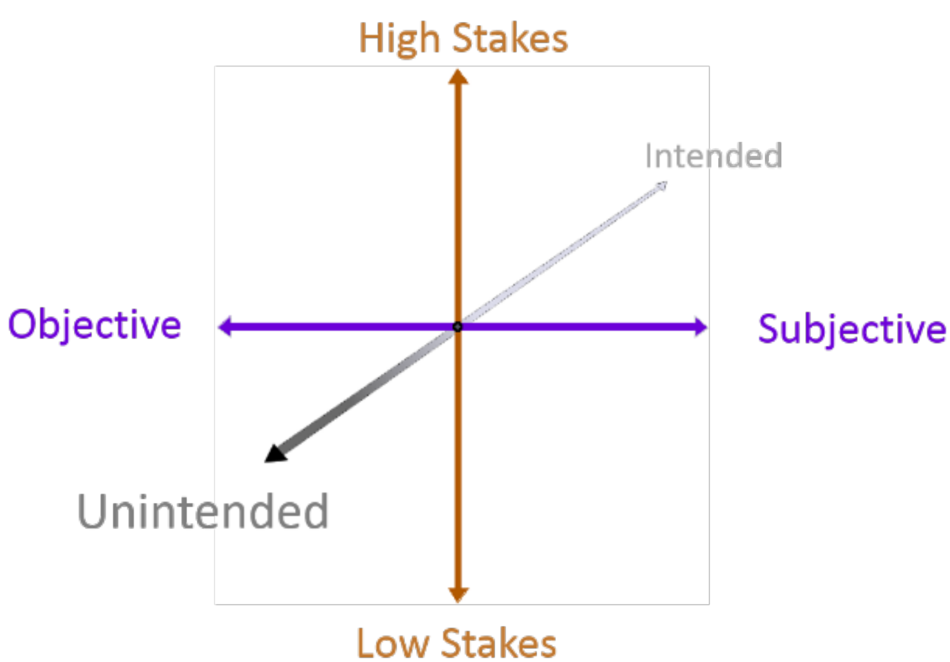

Figure 2. Failure can be classified on three distinct axes: stakes, intent, and referent, producing a total of nine failure types.

Table 1.
Descriptions of the failure types from Figure 1

Type	Description	
	Low	*High*
Stakes	During early phases Private (individual or within group) Time for subsequent improvement	During final presentation Public (teacher or whole class) Part of formal evaluation
	Intended	*Unintended*
Intent	Planned Testing limits	Unplanned Breakdown in performance
	Objective	*Subjective*
Referent	Does not achieve desired criteria within given constraints	Performance compared other groups Can meet specified criteria

Stakes. The audience and importance of the failure can determine the stakes for performance. Low stakes failures occur away from the public eye (e.g., when the audience is only a student or student group) and there is time for improvement before formal evaluation. High stakes failures occur in the public eye or when active testing functions as a final evaluation for a design.

Intent. Another important aspect of classifying failure is the intent. When a design is tested until it fails or if it fails in a certain (planned) way, it is intended failure. However, if the design is unable to achieve the required criteria or to remain within the given constraints, it is unintended.

Referent. Failure can be a matter of perception. When a design fails with respect to the given criteria, the failure is objective. In some cases, though, a design could be construed as a failure compared with others' designs and/or it is judged to be "not good enough." In those cases, the failures are subjective.

Table 2 captures how the 270 instances of failure in our video data were categorized. Although the row name references a teacher, this indicates that a failure occurred in this classroom, not necessarily that there was participation in the event by the teacher, since many of the failed attempts occurred during small group work without the teacher present.

Table 1.
Failure types coded by classroom

		Low stakes, Intended	Low stakes, Unintended	High Stakes, Intended	High Stakes, Unintended	Total
Cohort A	Thomas	29	14	5	2	50
	Maddux	6	2	1	5	14
	James	13	19	0	0	32
	Clay	25	4	6	2	37
Cohort B	Lyle	4	11	5	3	23
	Flemming	7	8	13	19	47
	Tanner	12	7	13	6	38
	Houseman	13	10	2	4	29
	Total	109	75	45	41	270

Coding instances of failure in the classroom video surfaced no obvious patterns in the numbers or types of failures associated with the curriculum used or across teachers. This is due in part to teachers implementing the civil engineering projects differently, despite common professional learning experiences. It is interesting to note that, except for Ms. James, who did not include an opportunity for students to share their work with the class, in every classroom, all four types of failure occurred.

Table 2 does not include coding for the *referent* axis because it is difficult to accurately code for subjective failure solely through video analysis of classroom discourse. Thus, our data only coded instances of objective failure, which we could observe; we limited our categorization of failure type to the combination of two axes, *stakes* and *intent*.

Failure has many facets. Categorizing the types of failure is an important first step. But classification alone does not promote the productive use of failure to inform improved designs. As we explored the nature of engineering failure with children, we also probed why designs fail.

Causes of Failure

An educator is likely to be more effective at helping students diagnose, learn from, and work through failure if they have a sense of why it happened. Thus, we were also interested in understanding more about the root causes for students' failed designs. We systematically analysed, coded, and recoded our "failure" video episodes for the causes for failure. Failure was caused by: (a) a lack of student understanding of science and/or technology, (b) a lack of student understanding of the materials, (c) poor craftsmanship, and (d) limitations of the materials that were used.

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To illuminate how failure and their causes may manifest themselves during elementary classroom lessons, we provide an example that highlights each type of cause. For these, we offer an example with word-by-word transcripts, including contextual (non-verbal) cues and timestamps.

Lack of understanding of science/technology. Rachel, Max, and Laura were challenged to design a bridge structure made out of 25 playing cards and 18 inches of tape that could hold as much weight as possible. Their first design failed to hold any weight. Their conversation about how to improve the design demonstrated that Rachel was basing her design on a technological misconception. Table 3 presents a transcript of the dialogue in this group.

Table 3.
Lack of understanding of science or technology

Time	Line	Laura	Max	Rachel	Contextual Cues
17:48	1 2 3			We need to put more support on it. This is the triangle base	Puts cards down with triangle on its side
	4 5		No, I was thinking something like…		Places two cards on top
	6 7			Ok, let's make another triangle base	
	8 9	We have all these cards			Holds up stack of other unused cards
 18:03	10 11			Ok, do another triangle	

Rachel insisted three times the group should use a triangle-shaped structure (lines 1-3, 6-7, 11). Perhaps she had heard of structural benefits of using triangles to distribute a load; however, placing the triangle on its side (i.e., placing all vertices of the triangle in a horizontal plane, with the load exerting its force perpendicular to that plane), eliminated that benefit. Her incomplete understanding of the distribution of forces contributed to their bridge's failure.

Lack of understanding of materials. Insufficient understanding of the properties of materials being used in the design also contributed to design failure. The group presented in Table 4 created a bridge that failed. Their first design used copy paper as the bridge deck. Their teacher, Ms. Clay, questioned the students (lines 24-28) to help them diagnose the cause of the failure. One member (Liam) recognized that the decking material (copy paper) they used was not strong enough and that craft sticks would have been a better choice (lines 32-33). In this case, the students in the group did recognize the need to use a strong material for deck construction.

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Table 4.
Lack of understanding of materials

Time	Line	Liam	Ms. Clay	Context Clues
23:53	24 25 26 27 28		Well, what's the problem? What would you have used? What do we know about spans? What do you want to have across the span?	Hand motions back and forth signalling the answer she's looking for that support goes across the whole span
	29	Um, the strongest material.		
	30 31		What would the strongest material be?	
24:08	32 33	What's it called, uh, craft sticks.		

Poor craftmanship. Poor craftsmanship is another cause for failure likely to be common, especially in elementary classrooms. Across all observed instances of construction in this study, no student ever measured the height of multiple bridge piers they constructed with a ruler to ensure the piers were cut to the same length and that this length was similar to the height of the abutments. Students deemed no measurement or "eyeballing it" sufficient. This resulted in students re-cutting piers to achieve a standard length. For example, in the transcript presented in Table 5, Riley identifies that she has "screwed up" by cutting all the piers too short—they will not be level with the abutment—and announces that the group will need to make new ones.

Table 5.
Poor craftsmanship

Time	Line	Liam	Libby	Riley	Context Clues
26:25	1 2			We need a whole new piece of paper	Crumples a pier in her hand
	3 4	Dang it. Huh?	What?		Both look up from the bridge
   26:35	5 6 7 8			A whole new piece of paper. I screwed up. I screwed up on all of them and made them too small.	Picks up other piers and drops them on the desk.

Limitation of materials. Finally, limitation inherent to materials may also cause failure. Designs may be based scientific concepts and use the best available materials. But these designs also can fail due to natural limits of materials. This failure is typically associated with intended failures, such as loading weight onto a structure until it collapses. In one bridge lesson, students

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Vol 7, No 2, December 2021, 69-92

gathered data about the strengths of three types of bridges—beam, deep beam, and arch—by constructing simple models and adding weights one by one until they collapsed. The transcript in Table 6 captures a brief interaction when two pairs of students (Ronnie and Rebecca, Louisa and Lenny) each test the beam bridge design to failure.

Table 6.
Limitation of Materials

Time	Line	Louisa	Ronnie	Rebecca	Context Clues
56:02	1 2 3			We got five	Both groups' beam bridges fail at the same time
	4	We got three			
	5 6 7			No, we got, we got four	She realizes it collapsed on the fifth weight, meaning it held four.
	8	Let's try that again			To Lenny
	9 10		Yeah, let's try that again		To Rebecca
   56:22	11 12 13 14	Do we try again, or not? Are we supposed to try it again?			To all students at the table. Both groups proceed with another trial

In this case, students were testing "given" prototypes until failure. Ronnie and Rebecca compared their testing results with Louisa (lines 1-5). Each bridge type should have performed similarly across groups, since the prototypes were provided to help students compare the strength of bridge types. The groups appeared to recognize that their bridges should support the same critical load, so when their results differed, they instinctively thought to retest and verify their measurement (lines 9-10 and 11-13).

Our careful analysis of failure episodes surfaced these general four causes. However, it was not always possible to determine the exact cause of a design failure. And, often more than one cause contributed to the failure.

Obstacles to improvement

Regardless of the type of failure or the reason(s) for it, the goal is to have productive failure—that is, the failure leads to opportunities for learning, which can be manifest through subsequent improved designs and/or a deeper understanding of the problem, science and technology concepts, property of materials, or better understanding of the causes of failure. However, productive failure and improvement are not inevitable. We examined our data to

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understand how students and teachers collectively support or constrain productive uses of failure. Our analysis identified three general obstacles that hinder improvement, success, and/or learning: unfair comparisons, insufficient opportunities, and unproductive strategies.

Unfair comparisons. The goals for engineering design tasks are often unclear, presenting challenges in both the initial design and subsequent iterations. For example, one lesson directed student groups to build a structure that was as tall as possible and could hold as many weights as possible. Because the task did not define either a minimum height or weight, it was challenging for students and teachers to understand what counted as success or failure. Was a 12-inch structure that holds 30 weights successful? How did that design compare with a 6-inch structure that held 35? Students were more likely to express *subjective* failure in such situations where the only measures were comparisons to other students' designs. A salient example of this was seen in Mr. Tanner's class after groups publicly tested their structures (see Table 7).

Table 7.
Unfair comparisons

Time	Line	Owen	Mr. Tanner
53:35	1 2	Did we get first, second or third place?	
	3 4 5 6 7		First, off, it was not a competition. Because if it was a competition, we would have had a lot more variables, such as height, because directions were a TALL structure, right? So it's not a competition, it's about how did your group do compared to what you predicted. So don't worry about first, second, third place. There was no prize.

Two interesting and related points arise in this teacher's response. First, Mr. Tanner recognized the limitation of the curricular instructions. His emphasis on "TALL" (line 5) also suggests he thought some groups did not build "tall" structures. The teacher communicated that success would be achieved if the structure held the amount of weight the group predicted. In such situations, however, the limitations in the directions made it difficult to evaluate improvement.

Unproductive strategies. Improvement can also be hindered by a lack of productive improvement strategies. Ideally, the specific weaknesses of a design can be identified. Future iterations then make relevant improvements. Our analysis indicated that many groups lacked observable, *productive* strategies for improvement, and their next iterations failed due to the four failure causes described above.

An example of an unproductive strategy is constructing the same failed design repeatedly though it yields no improvement. Although persistence is a desirable trait, some students seemed to exhibit this pattern because they lacked a better strategy. For example, during an individual

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student activity in which the students designed a "tall structure" with eight playing cards and a foot of tape, Ida quietly built and rebuilt a structure that was so weak it could not stand independently. She was very animated each time it fell and was clearly pleased when she was able to add a second layer. When she seemed to be stuck, she surveyed the room (presumably to see others' strategies). Although she seemed to have a strategy (persistence and learning from peers), she did not appear to recognize the need to connect the cards by notching them or using tape to enhance the structure's stability and strength.

Insufficient opportunity. Even if students have a clear goal and a productive strategy, improvement cannot occur without opportunity to do so. Teachers constantly face tensions between covering content or slowing down or remediating to improve learning. Given enough time, all students could build bridges that support 5 pounds for 30 seconds; but time is a valuable classroom resource. The time teachers devoted to the bridge design projects varied: Ms. Lyle's class spent 127 minutes, Mr. Tanner's 112, Ms. Flemming's 87, and Ms. Houseman's 83. Ms. Lyle made the decision aloud that the students needed more time to construct their bridges and allocated more time.

Ms. Flemming chose to extend the lesson an additional day because no group built a successful bridge the first day. In the next class period, not only did she give the groups a chance to improve their bridges and re-test, but she also held public conversations with each group about the improvements they might make, highlighting the benefits of a rigid deck and additional piers to support the load. As a result, each group showed improvement.

Redesigning after high-stakes failure is often curtailed due to limits on time and materials. However, improvement from low-stakes failure during the design process is an important opportunity that was not afforded in many of these classes. In some cases, teachers did not allow students to test their designs in their small groups. Table 8 captures the tension between the teacher's (Ms. Lyle) no-testing rule (which stemmed from her mistaken interpretation that the curriculum forbade it) and the students' desire for such low-stakes testing.

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Table 8.
Denying opportunity for low-stakes failure

Time	Line	Laura	Max	Rachel	Ms. Lyle	Contextual Clues
21:15	1 2 3				Now is this going to be attached, or just free-standing?	Waves her hand over the structure
	4 5 6			[Just kinda free-standing]	[Ok]	
	7 8 9 10 11	We can just see what it's gonna do				
	12 13 14		We already tested with putting that on			Points to some school supplies on the desk
	15 16 17				No testing, Max. Remember, no testing.	
	18 19		Well, we just put it on			
21:35	20				No, no testing Max.	Ms. Lyle laughs
10 minutes later, when the teacher is no longer with the group						
31:00	21 22 23 24		Wait, let me see something. I want to see if it can hold something			Grabs a journal from the desk
	25 26 27	[No! No testing!]		[No testing!]		Max backs away, crossing his arms
	28 29		I really wanna test it			
31:20	30 31 32 33 34 35 36 37	Like, after we're done, I really want to see will ###				

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Prior to Ms. Lyle's arrival the students tested the strength of their structure using school supplies as the load. Ms. Lyle's emphasized this is not allowed (lines 16-18, 21, Table 8). When she departed, Max again tried to test their structure, but the "no testing" rule was upheld by his group (line 26, second episode, Table 8). Thus, any improvements were based on speculation, rather than evidence.

These examples contrast differences in the types of opportunities the enactment of a curriculum can provide for student improvement after failure. These opportunities support productive strategies by allowing students to gain a better understanding of the material properties and the science concepts by offering events to analyse, in their group or by observing the designs of others. Interestingly, they also demonstrate the importance of teacher implementation of curricula; all four teachers in the Cohort B forbade testing at the group level, even though this was not stated in the teacher guide. By looking at obstacles to learning and improvement to failure, we can think about factors that can scaffold student learning and improvement from failure. Curricula and teachers need to provide opportunity for improvement, tests need to allow for fair comparisons to gauge improvement, and students need to engage in strategies that help them productively learn from and work through failure.

A model for failure and improvement

Our analyses led to the synthesis of a model of failure and improvement (Figure 2) to conceptualize the complicated process of improvement from failure in engineering design. In it, the types of failure are recognized, engineering design solutions may fail in elementary classrooms for any combination of four reasons, and learning and improvement from failure can be facilitated by three factors. Unproductive strategies to work through failure generally reflect the four causes of failure. However, if students are given the opportunity to systematically improve their prototypes by using several iterations of low stakes testing and improvement, fair comparisons, and productive strategies, they have the opportunity to learn from failure, which may lead to improved designs.

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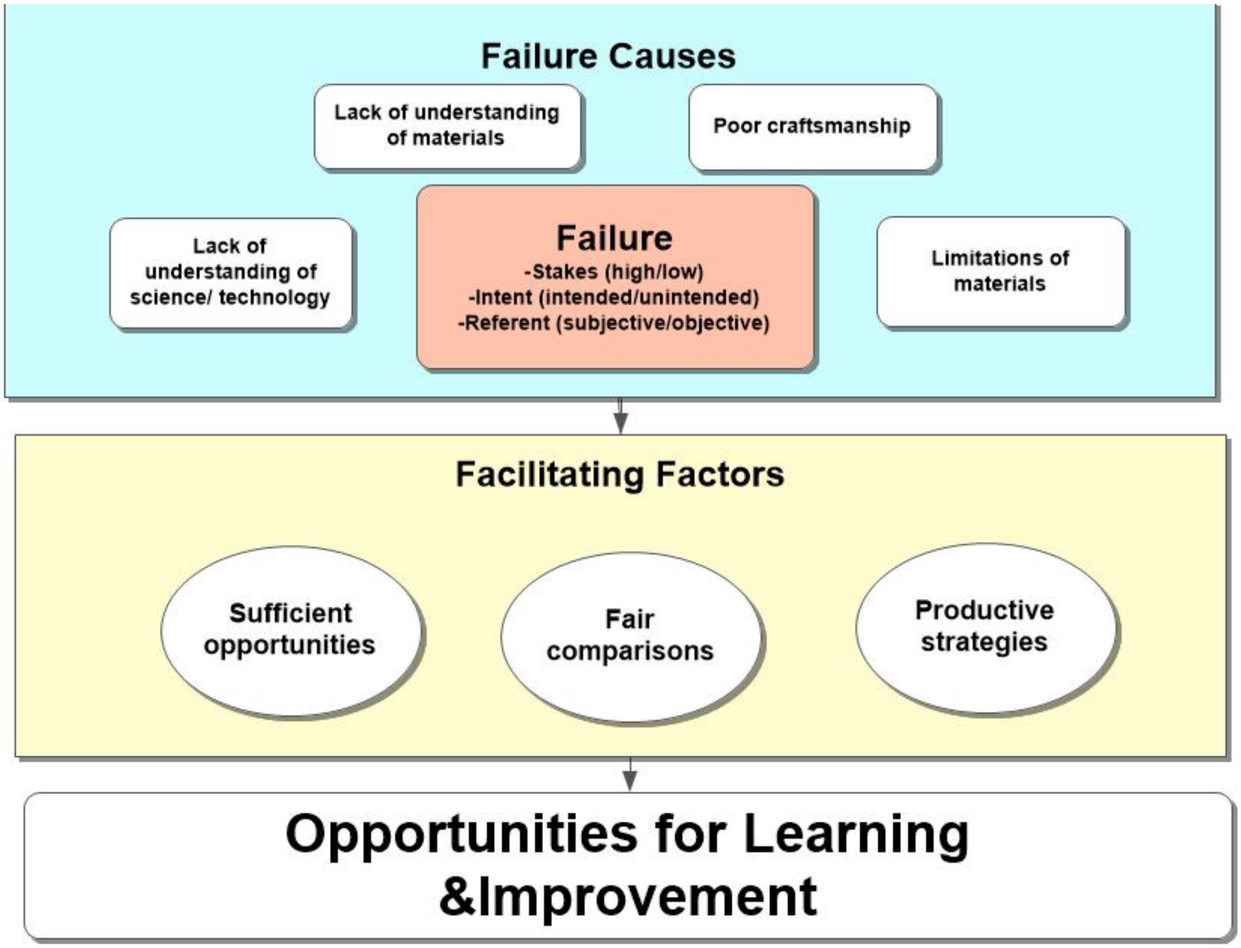

Figure 2. Learning and improving through failure in elementary engineering

In professional engineering, failed attempts are primarily steps on a path toward an improved design. However, the roles and outcomes of classroom engineering are more expansive (Norström, 2016). Of course, students all want to create improved designs when they fail. What is also important, however, is their oportunity to learn from their failure. Given the constraints in classrooms, such as time, some students might not ever create an improved technology. In some cases, a subsequent iteration might function worse than the prior one, but students learn additional valuable information about related science or engineering concepts, materials, or craftmanship, so the experience does meet important learning goals. In such instances, the learning is, perhaps, more important the the performance. In other cases, a haphazard decision might result in an improved design. If the student group fails to understand why the change occurred, a learning opportunity has been missed. Thus, a critical outcome in classrooms is providing students opportunities to learn from failure, whether or not they improve.

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Discussion

Learning from and persisting through failure is a key epistemic practice of engineering. However, traditionally, failure in clasrooms has been something to avoid in precollege classrooms. Thus, understanding how failure occurs in these settings and how classroom environments can be created that help students productively navigate failure is important. Features specific to the processes entailed in engineering design and the ways that classroom discourse mediates and constructs the epistemic practices of engineering were both found to be relevant to understanding how to learn from failure. We explore three features of engineering and three features of classroom cultures that contribute to learning to engage in productive failure.

Engineering design processes offer unique ways to learn from failure. First, learning engineering is more than knowing propositions about a stated design process; students need to engage in the practices of engineering. The materiality of engineering requires hands-on activities that allow students to balance a number of expected dimensions of the engineering design. Through the trials and tribulations of design, students need to wrestle with failure and recognize that their proposed solutions will not always work—sometimes a subsequent design may not out-perform the previous design. Students can learn valuable lessons about how to persist and overcome initial disappointing results.

Second, engineering design projects clearly benefit from having at least one cycle of improvement. They should encourage frequent low-stakes testing to enable students to learn and improve prior to high-stakes public tests. Student groups often move in fits and starts and take time to develop more systematic approaches. Opportunities to test materials, ideas, and craftmanship in low-stakes ways can help students develop more productive approaches. This feature of engineering is not unique to student work; rather, engineering across settings often requires multiple iterations of design, testing, failure, and improvement. Productive failure is more likely to occur when teachers and students come to realize that persistence in the face of frustration is part of doing engineering.

Third, engineering designs should be evaluated on multiple criteria and include constraints. This, of course, needs to be done in age-appropriate ways (Cunningham & Carlsen, 2014b). Engineering designs should balance tradeoffs. Asking students to consider several criteria, including some that are in tension, affords the opportunity for multiple solutions, many of which might initially fail. Thus, it also opens opportunities for all designs to be improved and for student learning. We propose that systematic improvement (that which relies on productive strategies) often demonstrates learning. This feature of engineering, like the others, while grounded in disciplinary practices, needs to be taken up and re-constructed in classroom

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discourse. Ways engineering is framed and epistemic practices appropriated depend on the classroom cultures.

Features of classroom cultures contribute opportunities to engage in productive failure. In the classrooms analysed in this study, three aspects of the classrooms contributed to the uses of failure for productive learning. First, engineering design and learning from engagement with materials were prevalent in each class. Elementary-aged children need the opportunity to engage in hands-on engineering design projects that require active learning (Banilower et al., 2006). Through experimentation and manipulation of physical materials, students come to construct meaningful understanding of science, technology, and materials properties. Focused learning activities, before or within engineering experiences, can help students understand the scientific and engineering concepts and materials required by the project. Such lessons develop craftmanship and fine-motor skills. They also provide more equitable learning experiences by providing opportunities for all student to construct background knowledge they can draw upon during the design challenges. Such scaffolding experiences can, in turn, decrease the number or degree of failures caused by lack of understanding of science, technology, and material properties. When failure does occur, the previous experiences can be referenced. In examples in this study where improvement occurred, the students were situated to collectively interpret the performance of their design and to propose and to enact improvements.

Second, while engagement with hands-on activity was important, it was not enough for learning. Engagement in design for the purposes of learning the knowledge and practices of engineering required a community context that supported the refinement of ideas. This suggests another important feature that supports failed attempts—the creation of a productive discourse community. The Cohort A teachers used the scaffolds included in the curricular materials to create social contexts for deliberation among students. Students learned from the experiments they conducted, from each other, and from other groups. Teachers in the classroom also played a series of critical roles (Johnson, 2019) to guide student through failure. They set up discourse communities and provided suggestions or feedback to promote improvement. Through participation in the discourse communities, students were able to recognize that designs were not always successful and, that by considering the reasons for failure, they could improve. An important part of situating students as learners from failure is recognizing the value of the collective reasoning. Students learned not only from their own projects, but from the work of other groups. This may both have removed some of the stigma of failing and provided insights into how, for example, tier bridges could be re-designed.

Third, teacher feedback can be a very powerful tool; therefore, teachers should carefully consider the types of interactions they have with students and the potential effects of each engagement. We observed positive results when teachers empowered students to collaborate and

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take ownership of their designs, and when teachers helped students identify the areas for improvement and consider strategies to achieve them. Sharing the common causes of failure with students and encouraging groups to diagnose the causes of failure in their attempts may help students develop productive strategies for improvement. This diagnosis can also be supported by teacher feedback. For example, one teacher engaged students in an analysis of specific ways in which their design fell short. In this class productive strategies involved manipulations of materials, engagement in substantive conversations about the function of the design, and consideration of how to make improvements to overcome the shortcomings, all of which were facilitated by the teacher.

Conclusion

Although improving from failure is an important aspect of engineering, precollege schools typically feature problem sets with correct answers and rarely present opportunities for students to improve. Engineering design projects not only provide an opportunity for students to learn and apply content (Katehi, Pearson & Feder 2009, NRC, 2012), but also emphasize the creativity involved in design and how learning from failure can lead to improvements (Katehi, Pearson & Feder, 2009). Failure is a complex topic, and requires new frameworks for communicating about the context, type, cause, and features that facilitate learning and improvement (Jackson et al, 2021). Ways that failure can serve for learning depend on the discourse around failure. Through interpretations of the role and purpose of failure, teachers can set students on the path to productive learning

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