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Recognition of Design Failure by Fourth Grade Students During an Engineering Design Challenge (Fundamental)

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Abstract

The practice of persisting and learning from design failures is essential to engineering design and offers unique ways of knowing and learning for K-12 students. To understand how students engage in the practice of persisting and learning from design failures, we must first understand how, if at all, they recognize that a design failure has occurred. We studied a classroom of fourth grade students engaged in an engineering design challenge and examined the ways in which design failure occurred and how students recognized, neglected to recognize, or misinterpreted design failure. In addition to anticipating failure, conducting fair tests, and making focused observations, we found that students must have an understanding and awareness of the evolving criteria and constraints of the design problem in order to recognize design failure. If lacking an understanding and awareness of criteria and constraints represents a barrier to recognizing an initial design failure, it also represents a barrier to recognizing any subsequent design failures in the design process and thus a barrier to persisting and learning from design failures.

Introduction

The introduction of engineering design in elementary education allows students to engage in a host of epistemic engineering practices such as envisioning multiple solutions to problems, iteratively designing and testing prototypes to optimize designs, working effectively in teams, and persisting and learning from design failures [1].

The practice of persisting and learning from design failures is essential to engineering design as engineering problems are rarely easily solved. Engineers often encounter unforeseen circumstances, impediments, and even changing criteria or constraints that lead to failure of designs. In fact, engineers value the opportunities that design failures provide for learning and improving designs [2], and the anticipation of how failure might occur is a critical element in successful design [3].

While engineers regard failure as an expected part of the problem-solving process, teachers tend to view failures as mistakes or errors. Lottero-Perdue and Parry [4] found that teachers in grades 3-5 had a negative view of failure in general and never or rarely used the word failure in their classrooms due to its negative connotation. Yet persisting and learning from failure is not only an important problem-solving skill, but a valuable life skill. This aspect of the process of engineering offers unique ways of knowing and learning that are not otherwise incorporated into K-12 education [1]. Understanding how students persist and learn from design failures can inform the development of curriculum and pedagogical strategies that support productive student learning and a positive teacher view of the learning opportunities presented by engineering design failure.

Persisting and learning from design failures is not a discrete practice but occurs over time throughout the engineering design process. Each identified design failure signals a new cycle through the iterative engineering design process in which a new problem is defined (the cause of the design failure), and the criteria and constraints of a solution (the remedy for the problem) are identified. Multiple design solutions to the new problem are envisioned and tradeoffs between criteria and constraints considered. Prototypes are iteratively created, tested, and revised to optimize a design solution that meets the defined criteria within the constraints. Finding a viable design solution to the original problem may require persisting and learning from multiple design failures as the iterative cycle repeats until all design failures are resolved.

In order to understand how students engage in the practice of persisting and learning from design failures, we must first understand how, if at all, they recognize that a design failure has occurred.

Background

Crismond [5] observed that high school students testing their imperfect prototypes often missed noticing their flawed performance and subsequently made few or no changes to their design throughout multiple design iterations. Sachs [6] referred to this widespread phenomenon observed in beginning and expert designers alike, where prototypes remain essentially unchanged from initial to final designs, as idea fixation, which represents a significant barrier to persisting and learning from design failures.

Using a protocol for assessing the actions of observing, diagnosing, explaining, and fixing associated with troubleshooting design failures, Crimsond [7] had high school students analyze different designs, make observations, identify flaws, and suggest remedies. The students frequently neglected to make observations and identify flaws and Crismond hypothesized that idea fixation is simply due to novices not noticing weaknesses in their current prototype.

In a subsequent paper, Crimson and Adams [8] stated that beginning designers use "an unfocused, non-analytical way to view prototypes during testing and troubleshooting of ideas" while informed designers "focus attention on problematic areas and subsystems when troubleshooting devices and proposing ways to fix them" [8, p. 749]. Their characterization of informed design strategies included understanding the challenge, building knowledge, generating ideas and representations, weighing options, conducting experiments, troubleshooting, iteratively revising, and reflecting.

Limited research has been conducted on how elementary school students diagnose and troubleshoot design failure. In a systematic review of literature on students' or teachers' experience with failure in design-related K-16 STEM education, Jackson *et al*. [9] found only seven studies focused on failure in engineering and only three studies in upper elementary grades [4], [10], [11].

One study of teacher reflections on student response to design failure found that upper elementary students engaged in engineering design did not always experience design failure and those who did, responded to design failure in a wide range of ways including denial that failure had occurred by ignoring proper testing procedures [4].

In addition to testing procedures that were ignored or test results that were not easily interpretable, this lack of design failure might also be explained by design challenges that were too easy and thus actually did not result in design failure [10], [12]. Through interviews conducted with kindergarteners after they engaged in engineering design, Lottero-Perdue and Tomayko [13] concluded that students had greater difficulty identifying design failures as the complexity and multi-faceted nature of the failures increased.

Most recently, Johnson *et al*. [14] analyzed the types and causes of design failure along with factors impeding productive learning from failure for 3rd-5th grade students engaged in an engineering design challenge. They distinguished three categories of design failure: stakes (low versus high), intent (unintended versus intended), and referent (objective versus subjective). Design failures were typically caused by a lack of understanding of science or technology, a lack of understanding of materials, poor craftmanship, and/or limitations of materials. In addition, they found that many students lacked productive strategies for improvement of designs, did not have sufficient time, and were more likely to express subjective failure when comparing their designs to other students' designs.

Conceptual Framework

The above studies examined types and causes of design failure, student and teacher response to design failure, and the troubleshooting aspect of informed design [4]-[14]. They identified making focused observations and conducting fair tests as important elements in recognizing design failure. We combined these elements with other epistemic engineering practices [1] to characterize "recognition of design failure" as a complex practice that requires students to engage in the following practices:

- Understanding all the criteria and constraints of the problem
- Anticipating or predicting failure in conceptual designs and/or constructed prototypes
- Making focused observations during all phases of design, construction, and testing
- Conducting fair tests and accepting the results of tests as evidence
- Realizing and acknowledging that at least one of the criteria or constraints is not met

Research Questions

In this study we used the above conceptual framework for recognition of design failure to investigate the following research questions:

1. What are the ways in which design failure occurred during an engineering design challenge with fourth grade students?
2. How did fourth grade students recognize design failure? (Correct identification of design failure)
3. How did fourth grade students neglect to recognize design failure? (False negative identification)
4. How did fourth grade students misinterpret design failure as having occurred when it had not? (False positive identification)

Research Context

MOXI, The Wolf Museum of Exploration + Innovation and the University of California, Santa Barbara (UCSB), are collaboratively developing and testing a suite of engineering-focused education programs that link engineering design challenges completed on field trips to the interactive science center to classroom science and engineering learning through pre- and post-field trip classroom activities [15]. Two engineering field trip programs, *Engineering Explorations*, were implemented with over 200 K-6 classrooms between September 2018 to March 2020. Seven additional programs are in various stages of development and testing. The pre- and post-field trip classroom activities for the fully developed programs were implemented by informal educators from MOXI in 27 classrooms from three focus schools that were selected to represent a range of demographics for local schools.

For each *Engineering Exploration*, the field trip activity plus two pre-field trip classroom activities and one post-field trip classroom activity constitute a full module. The first pre-field trip classroom activity engages students in a grade-level, standards-tied science experiment that lays the conceptual foundations for the engineering design challenge. The second pre-field trip classroom activity introduces students to the engineering design process, which is defined as having three stages: 1) Defining and delimiting an engineering problem, 2) Developing possible solutions, and 3) Optimizing the design solution. Students engage in this process at increasing levels of sophistications in all K-12 grade levels [16]. The field trip to MOXI, occurring third in the sequence of four activities, engages students in an authentic engineering design challenge that has ties to and makes use of the resources and exhibits of the interactive science center. The fourth activity in the module, the post-field trip classroom activity, is a reflective activity that ties the first three activities together and links back to school standards. Each activity is completed in 50 minutes.

This study focused on the second pre-field trip classroom activity for one of the fully developed engineering field trip programs, *Riding the Rising Air*. In the first pre-field trip classroom activity, students used paper and tape to build three sizes of parachutes to slow the fall of a metal washer the size of a penny. They conducted an experiment to determine a relationship between the size of the parachute and the rate fall of the metal washer. In the second pre-field trip classroom activity, students used the knowledge gained in the first activity to design and test multiple models of a vehicle, constructed from a single piece of paper and masking tape, that carried a metal washer the size of a penny to the ground as slowly as possible when dropped. The activity occurred in three rounds:

1. An initial individual design in which the students tested their designs against a bare metal washer [test criterion 1].
2. A group design in which teams of 3-4 students combined ideas from the first round to create and test three iterations of a collaborative design, each time trying to improve the design by further slowing the fall of the vehicle compared to the previous design [test criterion 2].
3. A final individual design to incorporate ideas from the first two rounds and produce a final design solution that fell slower than any other prototype vehicles [test criterion 3].

Participants

During the spring of 2019, the pre-field trip lessons for the *Engineering Exploration*s curriculum were taught by informal educators from MOXI as part of a grant-funded outreach program at two elementary schools in Santa Barbara County, California. The classes selected for participation in the program were selected by the school principals based on interest for participation by the teachers. Three first grade and three fourth grade classes from Camino Elementary School (pseudonyms are used for participating schools) and three fourth grade classes from Peralta Elementary School participated for a total of 270 students. The demographics of participating students from Camino Elementary were representative of students attending Camino Elementary which reports 53% Latinx, 42% Caucasian, 3% Asian, 1% African American, and 1% other. The demographics of participating students from Peralta Elementary were representative of students attending Peralta Elementary which reports 78% Caucasian, 13% Latinx, 7% Asian, 1% African American, and 1% other. Camino Elementary School students most closely matched the demographics of interest and the fourth-grade classes most closely matched the research study goals of examining recognition of design failure in upper elementary students. Of the three Camino Elementary classrooms, one fourth grade class of 24 students was randomly selected for analysis.

Data Collection

The data analyzed here were collected as part of a larger multi-year design-based implementation research study. Consistent with design-based implementation research [17], a variety of types of data were collected. Video recordings of the field trip programs and classroom activities were collected for all of the participating school classes along with field notes, samples of student work, and teacher and facilitator interviews. The video recordings were captured from both fixed and roving cameras and included clips ranging from 12 seconds to over 38 minutes in length. While fixed camera locations were typically chosen to capture as broad a field of view as possible, video was sometimes collected by the people facilitating the activities, changing the camera perspective for roving shots to the perspective of the facilitator. No supplemental lighting was used. Audio was recorded through the camera microphones. In addition, still images were captured to show both general activity and record artifacts of student work, including sketches of designs and prototypes.

Data Analysis

Data were analyzed using an approach to discourse analysis grounded in ethnography and interactional sociolinguistics, for example [18]-[20], to investigate how students engaged in an engineering design challenge articulated recognition of design failure through their language, actions, and gestures.

Data processing and design failure event identification

The initial set of collected video recording data (53 minutes and 36 seconds) was examined to identify instances of design failure using the following criteria:

- Failure explicitly called out (e.g., spoken words indicating a failure – use of the word fail or failure, “it won’t/didn’t work, that’s not right, I lost/you won”)
- Material failure (e.g., indication that materials have failed – paper torn, tape stuck together)
- Emotional response (e.g., actions, gestures, facial expressions, or body language indicating frustration, defeat, sadness, giving up – throwing hands in the air, rolling eyes, lowering head, putting head on desk, expressing anger or sadness, crying, wadding up/throwing materials)
- Failed test (e.g, a test that does not test for the problem criterion – no bare metal washer or previous design, a tabletop test, no test before moving to next design iteration)

In addition to examining video recordings, the students’ hand-drawn designs were examined to identify instances in which the features of one drawn design did not appear in subsequent drawn designs (each of the three design rounds began with a hand-drawn design). These separate artifacts provided evidence of design abandonment, which was used to infer instances of design failure and identify additional video clips. Since 13 of the 24 hand-drawn designs could not be matched to students in the video clips (no name or illegible name on drawn design; named student could not be identified in video), specific design types that were commonly abandoned in the drawn designs were identified (e.g., paper airplane designs). All students constructing such designs were identified in video clips and their design evolution was examined through multiple video clips over time across the three design rounds. In other cases, when matching drawn designs to specific students was possible, the design evolution of those students was also examined through multiple video clips over time across the three design rounds.

The analysis described above limited the video to only those video clips identified as showing design failure events (20 clips totaling 32:51 minutes). These clips were then transcribed for spoken words, observations of gaze orientation, spatial-orientational arrangement, facial expression, gesture, and body posture. Several video recordings that captured a broad view of the entire class resulted in multiple design failure clips following specific students within the camera frame. Descriptions of actions of the subjects of the video clips were also included. This transcribed data set of design failure events was the data set analyzed.

Stage 1 analysis – Identifying types of design failure

The transcribed data set of design failure events was analyzed holistically using spoken words, observations of gaze orientation, spatial-orientational arrangement, facial expression, gesture, body posture, and descriptions of actions. Emergent coding of the data set produced five types of design failure presented in Table 1.

Table 1
Emergent Codes for Types of Design Failure

Types of Design Failure	Description
Material Failure	Paper tearing or masking tape unexpectedly sticking to itself or to the paper
Constraint Failure	Running out of time or materials
Failure of a prototype to meet the design criterion	In a fair test of a prototype dropped from one meter height, the vehicle fails to fall slower than a bare metal washer (round 1 criterion), the round 1 individual designs (round 2 criterion), or the slowest prototype from round 2 design iterations (round 3 criterion)
Predicted design failure	Spoken words indicating prediction of a failure
No Failure	Emotional responses indicate a student-identified failure event, but subsequent examination reveals no researcher-identified failure event

Stage 2 analysis – Identifying type of recognition of design failure

The transcribed data set of design failure events was examined to find multiple examples, for each type of design failure, of the types of recognition of design failure outlined in research questions 2-4:

- Student recognizes design failure (correct identification)
- Student neglects to recognize design failure (false negative identification)
- Student misinterprets design failure as having occurred when it has not (false positive identification)

Stage 3 analysis - Identifying practices that support recognizing design failure

Each of the 20 examples identified in the stage 2 analysis was coded using a priori coding for the practices supporting recognizing design failure outlined in the conceptual framework. Each practice, presented in Table 2, was classified as either present, absent, unknown, or not applicable.

Table 2
Practices that Support Recognizing Design Failure

Code	Practice that supports recognizing design failure	Description
UCC	Understanding all criteria and constraints	Understanding and awareness of all the criteria and constraints of the problem
APF	Anticipating or predicting failure	Anticipating or predicting failure in conceptual designs and/or constructed prototypes
MFO	Making focused observations	Making focused observations during all phases of design, construction, and testing
CFT	Conducting fair tests	Conducting fair tests and accepting the results of tests as evidence
RCC	Realizing a criterion or constraint is not met	Realizing and acknowledging that at least one of the criteria or constraints is not met

A sample of a short segment of a fully coded video clip showing instances of design failure is presented in Table 3.

Table 3
Sample of Coded Data

Clip #1		Time	1:00	1:03	1:05	1:07	1:09	1:12
Data Processing	**Transcription**	**Description**	Students U and V in conversation about U's design	“	“	“	“	“
		Spoken Words	U: No, no we're going to tape it so it doesn't open up. V: (inaudible)	U: I'll show you. V: (inaudible)	U: No because the washer will just fly straight out	U: When you throw it.	U: It will fly out backwards from the top.	U: We'll tape that part so it won't fly out.
		Spatial-orientational Arrangement	U and V facing each other across table	“	“	“	“	“
		Gaze Orientation	U & V looking at each other's faces	“	“	U looks at airplane	U looks back at V	“
		Gesture	-	-	U sweeps right hand across left hand which is palm up	U makes paper airplane throwing motion with right hand	U's right hand reaches up and pulls straight down	-
		Body Posture	U sitting back against his chair, V sitting upright against the table	“	“	“	“	“
		Facial Expression	U: relaxed, V: face not visible	“	“	“	“	“
Stage 1	**Type of Failure**	**Material**	-	-	-	-	-	-
		Constraint	-	-	-	-	-	-
		Prototype Doesn't Meet Design Criteria	-	-	-	X	-	-
		Predicted Design Failure	-	-	X	-	X	-
		No Failure	-	-	-	-	-	-
Stage 2	**Type of Recognition**	**Student Recognizes Failure**	-	-	X	-	X	-
		Student Neglects to Recognize Failure	-	-	-	X	-	-
		Student Misinterprets Failure	-	-	-	-	-	-
Stage 3	**Practices Supporting Recognition**	**Understanding of all Criteria & Constraints (UCC)**	-	-	Observed Present (vehicle must carry washer)	Observed Absent (doesn't understand vehicle must be dropped)	Observed Present (vehicle must carry washer	-
		Anticipating or Predicting Failure (APF)	-	-	Observed Present (verbal prediction)	-	Observed Present (verbal prediction)	-
		Making Focused Observations (MFO)	Observed Present (identifies problem area)	-	-	-	-	Observed Present (identifies problem area)
		Conducting Fair Tests (CFT)	Not applicable (test not conducted)					
		Realizing a Criterion or Constraint is not Met (RCC)	-	-	Observed Present (recognizes washer falling out as a problem)	Observed Absent - doesn't realize throwing violates criteria for a fair test	Observed Present (recognizes washer falling out as a problem)	-

In this case the student correctly recognizes and predicts a design failure (washer falls out of vehicle) but neglects to recognize that the prototype doesn't meet the design criterion as his intention to throw the paper airplane violates the criterion for a fair test.

Findings

Here we present examples identified in the stage 2 analysis of the ways in which design failure occurred during an engineering design challenge with fourth grade students according to the types 1-4 of design failure outlined in Table 1. Within each type of design failure, we provide examples of how fourth grade students (1) recognized design failure (correct identification of design failure), (2) neglected to recognize design failure (false negative identification), and/or (3) misinterpreted design failure as having occurred when it did not (false positive identification). For each example, we present the stage 3 analysis, applying the conceptual framework to examine evidence indicating engagement or lack of engagement in the practices that support recognizing design failure.

Material failure

Observed material failure consisted of paper tearing or masking tape unexpectedly sticking to itself or to the paper. The examples of material failure all involved parachute designs in which students recognized material failure. There were no observed instances of students neglecting to recognize or misinterpreting material failure. Four students created initial design prototype vehicles that duplicated the parachutes they created in the first pre-field trip classroom activity by making a parachute canopy out of the sheet of paper and parachute shrouds out of strips of masking tape. Two of these students experienced material failure as outlined below.

Recognizing material failure

Example 1: During round 1 individual designs, one student's masking tape shrouds stuck to the paper canopy and tore the canopy when they were removed (student K, table 4, clip 3, 2:27-3:00). He recognized and responded to this material failure by dramatically rolling his eyes, throwing his head back, and putting his head down on the table repeatedly (Fig. 1).

Fig. 1. A student recognizes a material failure and responds with emotion.

In this example, student K made a focused observation that the paper had torn (MFO observed present). From his emotional response we infer that he anticipated or predicted design failure (APF inferred present) and realized that he could not meet at least one of the criteria and constraints of the problem with a torn piece of paper (RCC inferred present). This example did not include any testing of a prototype (CFT not applicable) and it is not possible to determine if he had a complete understanding of the criteria and constraints of the problem (UCC unknown).

Example 2: In the same round (round 1 individual designs), a tablemate of student K, also constructing a parachute prototype vehicle, had similar difficulties with the masking tape shrouds sticking to themselves (student L, table 4, clip 3 0:54-1:05). Recognizing this material failure, he responded by removing the shrouds, wadding them up into a ball and throwing it onto the floor. He then started over on the construction of his prototype. Twice he twisted his torso towards his tablemate (student K) and oriented his gaze towards the tablemate's vehicle while the tablemate struggled with a material failure (clip 3 2:30, 2:52). During these episodes the two students appeared to be talking to each other, but their conversation was not audible on the video recording. In his new design, student L constructed shrouds by placing the sticky sides of two pieces of tape together to eliminate the problem of shrouds having a sticky surface. Whether he recognized this material failure during his own or his tablemate's failure (or both), he eventually found a remedy to the problem.

In this example, student L made focused observations that the masking tape shrouds stuck together on both his and his tablemate's vehicles (MFO observed present). In removing the stuck shrouds and creating new shrouds with less sticky surface area we infer that he anticipated or predicted design failure (APF inferred present) and realized that he could not meet at least one of the criteria and constraints of the problem with sticking shrouds (RCC inferred present). This example did not include any testing of a prototype (CFT not applicable). Because the student went on to complete a prototype vehicle that met the criteria within the constraints of the problem (clip 9, 1:21), we infer that he did have a complete understanding of the criteria and constraints of the problem (UCC inferred present).

Constraint Failure

Failures involving constraints included students running out of time or running out of materials and being unable to complete the construction or testing of their vehicles. Five instances of constraint failure were observed. In three examples students recognized constraint failure and in two examples students failed to recognize constraint failure.

Recognizing constraint failure

Example 3: In one case of constraint failure during round 1 individual designs, materials were removed when the building time had expired (clip 4, 5:23). A student, who had talked about needing to tape up the end of her paper airplane to prevent the washer from falling out, resorted to rolling the two edges of paper together and twisting the corners as a solution to the problem of no longer having tape, quickly eliminating the constraint failure caused by lack of materials (student X, table 7, clip 4, 4:56-7:41).

In this example, student X made a focused observation that the tape had been removed by the facilitator before she was able to complete her construction (MFO observed present). Given her attention to her tablemates' discussion of the potential problem of the washer falling out the back of the airplane (students U and V, Table 7, clip 4, 1:00-1:12) and her solution to the changed constraint of not having making tape, we infer that she anticipated or predicted design failure (APF inferred present) and realized that she could not meet the criterion of having the vehicle carry the washer if the washer fell out of the airplane (RCC inferred present). She did two drop tests of her vehicle above the table (clip 4, 8:44, 8:47) to test the functionality of her solution to keep the washer in the vehicle (CFT observed present). Note that while a test of the vehicle against a bare metal washer was not observed, her tabletop tests constituted a fair test of her solution to the constraint failure. Based on her design and construction, her tabletop tests, and her attentiveness in listening to the testing procedure instructions (clip 4, 6:10-6:58) we infer that she had a complete understanding of the criteria and constraints of the problem (UCC inferred present).

Example 4: The student who experienced material failure in example 1 when his paper tore in half subsequently experienced constraint failure as a constraint of the problem was that each student was given one piece of paper (student K, table 4, clip 3, 2:50). He eventually taped the two pieces of paper back together (clip 3, 6:38) and conducted what appeared to be a test designed to demonstrate failure. He held his repaired paper up sideways above the table and dropped it while staring intently at his tablemate (clip 3, 6:53). He subsequently gave up on the activity and sat in isolation until the end of the design round (clip 3, 7:00-8:53) instead of testing a vehicle with his tablemates (Fig. 2).

In this example, student K made a focused observation that the paper had torn (MFO observed present). In giving up on the activity, we infer that he anticipated or predicted design failure (APF inferred present). Since he did not ask for an additional sheet of paper and tried to repair the torn piece of paper, we infer that student K realized that he could not complete a successful design given the constraint of having only one piece of (damaged) paper (RCC inferred present). His test of the functionality of his repaired piece of paper was not a fair test as it was not formed into any sort of prototype vehicle, and it did not carry a washer (CFT observed absent). It is not possible to determine if he had a complete understanding of the criteria and constraints of the problem (UCC unknown).

Fig. 2. A student, recognizing a constraint failure due to a torn piece of paper conducts a tabletop test, displays emotion, and sits in isolation during the rest of the individual design round.

Example 5: This same student during the round 2 group design was very aware of the time constraint and was quite vocal and pessimistic in his prediction of constraint failure (student K, table 4, clip 16, 0:40-1:26):

> He told his teammate, student L:
> "Literally, you've been wasting all of our time."

He then pressed student L to test the design:
"Do it. Test it. Right now."
Student L conducted a functional drop test of the vehicle by itself, and student K declared it a failure:
"See. See. You failed."
Student K reiterated the time constraint:
"There's only one minute left."
The facilitator interjected:
"There's plenty of time in one minute."
He responded with:
"We can't do anything about it now."
"You can't change it."
"There's not enough time."

In this example, student K made a focused observation that the group did not have enough time to complete changes to the design (MFO observed present) and he verbally predicted constraint failure (APF observed present). He realized and vocalized that they could not change the design given the constraint of limited time (RCC observed present). Although he used the test of functionality of the design as evidence confirming the need for a design change, the test was not a fair test as the vehicle was tested by itself and not against a previous design (CFT observed absent). Given that he accepted the functionality test as evidence of the need for a design change, we infer that at this point he did not have a complete understanding of the criteria of the problem (UCC inferred absent).

Neglecting to recognize constraint failure

Example 6: In the previous example, the teammate doing the construction of the prototype vehicle, student L, did not seem concerned about the time constraint, despite his teammate's predictions of failure (student L, table 4, clip 16, 1:30-3:19). In the remaining 1 minute and 49 seconds he created two more design iterations – a sheet of paper curled over with the long edges taped together at two points without a washer attached and a flat sheet of paper with a washer taped in the middle. Student L conducted tabletop drop tests of both designs (clip 16, 2:45, 3:11). After the final drop test, he turned to his tablemate, student M, smiled and said, "there you go" (clip 16, 3:14). Although he seemed pleased that he had created two additional designs in the small amount of time remaining, he did not conduct fair tests of the designs or use observations from the tests to inform any design changes in the iterative optimization of the design. In this case, awareness of a constraint failure was not shared by all members of the team.

In this example, student L ignored his teammates observation that the group did not have enough time to complete changes to the design (MFO observed absent) and by his actions of completing three designs in the allotted time, we infer that he did not predict that he would fail due to a time constraint (APF inferred absent). Given his comment and attitude at the end of the group design round and the fact that his second design did not carry a washer, we infer that he did not realize or acknowledge that at least one of the criteria or constraints was not met (RCC inferred absent). Although he conducted tabletop tests of functionality of the designs, neither was a fair test as the vehicles were tested by themselves and not against a previous design (CFT observed absent).

Given his lack of fair tests and the fact that his designs were not iterations on the previous design, we infer that he did not have a complete understanding of the criteria of the problem (UCC inferred absent).

Example 7: In one case of constraint failure during round 2 group designs, one group clearly neglected to recognize a time constraint as they created only a single design, neglected to conduct any tests, and spent most of their time talking (students H, I, J, table 3, clip 11, 3:56-7:45).

In this example, given the amount of time spent talking versus working on the design challenge we infer that the table 3 students did not observe the time constraint (MFO inferred absent), did not predict that they would fail due to a time constraint (APF inferred absent), did not realize or acknowledge that at least one of the criteria or constraints was not met (RCC inferred absent), and did not have a complete understanding of the criteria of the problem (UCC inferred absent). In addition, they did not carry out any testing of their single design, even a tabletop drop test (CFT observed absent).

Failure of a prototype to meet a design criterion

Recognizing failure of a prototype to meet a design criterion required conducting a fair, precise test and making good observations of aspects of the prototype vehicle behavior relevant to the design criterion. Students first needed to remember that the main criterion of the problem was for the vehicle to fall slower than another specific object (bare metal washer in round 1 or previously designed vehicles in rounds 2 and 3).

Recognizing failure of a prototype to meet a design criterion

Example 8: During the round 1 individual designs a student, conducting a tabletop drop test of functionality, noticed that the weight of the washer in the nose of her paper airplane caused it to fall nose first, a much faster-falling orientation (student X, table 7, clip 4 8:25-8:48). While her actual drop test against a bare metal washer was not observed, we re-created a drop test of her design, in which a paper airplane with a metal washer in its nose fell consistently at the same rate as a bare metal washer. Her comment during the tabletop tests to her tablemate, student W, that the plane "fell to this side, like this" when dropped indicates recognition of a problem (clip 4, 8:47). Whether she confirmed that problem during a subsequent fair test against a bare metal washer or inferred that the problem would result in not meeting the design criterion, she abandoned the design in her subsequent design iterations.

In this example, student X made a focused observation that the position of the metal washer in the nose of the airplane caused it to fall nose down (MFO observed present). Given her verbal comment to her tablemate and the fact that she abandoned the design in future design iterations, we infer that she anticipated or predicted design failure (APF inferred present) and realized that she could not meet the criterion of having the vehicle fall slower than a bare metal washer (RCC inferred present). Since the groups' testing of prototypes against a bare metal washer was not observed it is not possible to determine if a fair test was conducted (CFT unknown). Based on her design and construction, her tabletop tests, and her attentiveness in listening to the testing procedure instructions (clip 4, 6:10-6:58), we infer that she had a complete understanding of the criteria and constraints of the problem (UCC inferred present).

Example 9: Eight out of 24 students chose to draw a paper airplane as their round 1 individual hand-drawn design and 12 of 24 students constructed paper airplane vehicles as their round 1 individual design prototypes. If the students intended these vehicles to operate as gliding airplanes their designs would fail to operate as intended because the criterion for a fair test specified that the vehicle must be dropped and not thrown. Only one of the students who initially drew a paper airplane design drew subsequent variations of the original design. From this lack of paper airplane-like features in subsequent designs, we infer that at some point these students recognized that the paper airplane design would not function as intended when dropped. Since no student drew a paper airplane design and then erased it to draw a different design or drew a paper airplane design but constructed a different prototype vehicle design, we assume the design failure of the paper airplane design was recognized during prototype testing and not during the conceptual design phase.

In this example, it is unknown if any of the students made a focused observation related to the failure of their vehicle to meet a design criterion (MFO unknown) or anticipated or predicted design failure (APF unknown). Since 11 out of the 12 students who constructed paper airplane vehicles abandoned their designs in subsequent design rounds, we infer that at some point they realized and acknowledged that at least one of the criteria or constraints was not met (RCC inferred present). Since the students' testing of prototypes against a bare metal washer was not observed it is not possible to determine if a fair test was conducted (CFT unknown). It is also not possible to determine if any of the students had a complete understanding of the criteria and constraints of the problem (UCC unknown).

Neglecting to recognize failure of a prototype to meet a design criterion

Example 10: During the design phase of the round 1 individual designs one student neglected to recognize a design failure because he designed a paper airplane which he intended to test by throwing instead of dropping (student U, table 7, clip 1, 1:00-1:12). At one point he tells his tablemate that the "washer will just fly straight out when you throw it" (clip 1, 1:07).

In this example neither he nor his tablemate make any observation relevant to the failure of the paper airplane to meet a design criterion when it is thrown and not dropped (MFO observed absent). They do not predict failure of the prototype to meet a design criterion (APF observed absent) nor do they realize or acknowledge that at least one of the criteria or constraints was not met (RCC observed absent). Clearly, they did not have a complete understanding of the criteria of the problem (UCC observed absent). Since this discussion occurred during the design phase, not testing was conducted (CFT not applicable).

Example 11: During the testing phase of the round 1 individual designs, one student was observed testing his paper airplane by throwing it (student P, table 5, clip 7 1:10-1:14). The student throws his paper airplane from the crouched stance of a dart thrower, stands upright with his shoulders back, turns and looks at the facilitator, smiles, interlocks his fingers, turns his wrists out and extends his arms in a show of satisfaction and accomplishment (Table 4).

Table 4
A Student Neglects to Recognize Failure

Clip #7		Time	1:10	1:14
Data Processing	Transcription	**Description**	Student P tests his paper airplane design by throwing it	Student P seems pleased with the results of his test despite the washer falling out of the vehicle, which he does not appear to have observed
		Spoken Words	-	-
		Spatial-orientational Arrangement	P stands at edge of classroom and faces the direction he is throwing the airplane	P rotates torso towards facilitator
		Gaze Orientation	P watches airplane	P looks at facilitator/camera
		Gesture	-	P interlocks fingers, turns wrists out and extends arms
		Body Posture	P – shoulders forward, crotched like dart thrower	P stands upright with shoulders back
		Facial Expression	P - concentration	P - smiles
Stage 1	Type of Failure	**Material**	-	-
		Constraint	-	-
		Prototype Doesn't Meet Design Criteria	Vehicle is thrown, not dropped	Vehicle fails to carry washer
		Predicted Design Failure	-	-
		No Failure	-	-
Stage 2	Type of Recognition	**Student Recognizes Failure**	-	-
		Student Neglects to Recognize Failure	X	X
		Student Misinterprets Failure	-	-
Stage 3	Practices Supporting Recognition	**Understanding of all Criteria & Constraints (UCC)**	Observed Absent (P does not understand the criterion for a fair test despite just being told to drop and not throw his airplane design)	-
		Anticipating or Predicting Failure (APF)	-	-
		Making Focused Observations (MFO)	-	Observed Absent (P has not made focused observations because in a separate video he is seen retrieving his plane and picking up the washer that fell out during the test. Since he seems pleased, at this point he must not have observed that the washer fell out)
		Conducting Fair Tests (CFT)	Observed Absent (P does not conduct a fair test)	-
		Realizing a Criterion or Constraint is not Met (RCC)	Observed Absent (P does not realize that by throwing the vehicle he has failed to meet the criterion)	Observed Absent (P appears pleased with the test and does not realize that his design has not met the criteria of the problem)

A student neglects to recognize failure of a prototype to meet the design criteria of being dropped and carrying a metal washer all the way to the ground.

In this example the student does not make any observation relevant to the failure of the paper airplane to meet a design criterion when it is thrown and not dropped (MFO observed absent). We infer that he did not predict failure of the prototype to meet a design criterion prior to the test (APF inferred absent). He did not appear to realize or acknowledge that at least one of the criteria or constraints was not met (RCC observed absent). Again, clearly, he did not have a complete understanding of the criteria of the problem (UCC observed absent), and he did not conduct a fair test (CFT observed absent).

Example 12: The same student also neglected to observe that his vehicle failed to carry the metal washer all the way to the ground (student P, table 5, clip 7, 1:10-1:14). His demeanor after the test implies that he is pleased with the test and does not realize that his design has not met the criteria of the problem (Table 4). Yet when he is seen retrieving the vehicle, he picks up the washer off the ground separately from the vehicle and places it back inside of the paper airplane (clip 17, 1:59-2:05).

In this example the student did not observe the failure of the paper airplane to carry the washer (MFO observed absent). We infer that he did not predict failure of the prototype to meet a design criterion prior to the test (APF inferred absent). At the time of the test, he did not appear to realize or acknowledge that at least one of the criteria or constraints was not met (RCC observed absent). It is not clear whether he recognized the design failure after the test since he placed the washer back in the paper airplane the same way. Again, clearly, he did not have a complete understanding of the criteria of the problem (UCC observed absent), and he did not conduct a fair test (CFT observed absent).

Example 13: Three students tested their group design prototype from round 2 against a bare metal washer when it should have been tested against their round 1 individual vehicles (students A, B, C, table 1, clip 13, 0:09-1:07). This example is similar to what happened in two other groups (students R, S, and T, table 6, clip 12, 0:49-1:22; students N, P, and Q, table 5, clip 14, 0:00-0:55). Students A, B, and C conducted five tests, consistently dropped the washer and vehicle at the same time from the same height and concluded that their vehicle fell slower than a bare metal washer (criterion 1). However, they neglected to recognize the failure of their prototype to meet the design criterion because they were not aware that the fair test criterion had changed and in this design round and they should have been testing against their individual design round vehicles (criterion 2).

In this example the students did not make any focused observations relevant to recognizing a failure of the prototype to meet a design criterion (MFO observed absent). We infer that they did not predict failure of the prototype to meet a design criterion prior to the test (APF inferred absent). They did not appear to realize or acknowledge that at least one of the criteria or constraints was not met (RCC observed absent). They did not appear to have a complete understanding of the criteria of the problem as they were unaware of the changed criterion for a fair test (UCC observed absent). Although this group conducted a very careful and precise test with one person holding the meter stick another person counting, and another person dropping the vehicle and the metal washer from the same height, they did not conduct a fair test because they should have been testing against a previously designed vehicle and not the metal washer (CFT observed absent).

Example 14: There were several instances of tabletop testing in which the round 2 group designs were not additionally tested from a one-meter height against a previous design but were simply dropped a few feet above a table surface (students U and V, table 7, clip 11, 3:58-7:43; student L, table 4, clip 16, 2:45, 3:11). While it is considered a good practice in engineering to "test early and often," these specific tabletop tests, which oftentimes were used in other situations as rapid tests of functionality and expected performance (e.g., example 3), were used as evidence of meeting the design criterion, so that any failure that might have occurred during a fair test was not observed.

In these examples the students did not make focused observations relevant to recognizing a failure of the prototype to meet a design criterion (MFO observed absent). It is unknown if they predicted failure of the prototype to meet a design criterion prior to the test (APF unknown). They did not appear to realize or acknowledge that at least one of the criteria or constraints was not met (RCC observed absent) and they did not appear to have a complete understanding of the criteria of the problem as they appeared to accept the results of the tabletop tests as evidence of having met the criteria and constraints of the problem (UCC observed absent). These tabletop tests were not fair tests of the problem criteria (CFT observed absent).

Misinterpretation of failure of a prototype to meet a design criterion

Two students appeared to recognize design failure when designs did not behave as they intended, even though the design met the criteria of the problem.

Example 15: - During a test of a round 1 individual design one student's vehicle rotated as it fell. From his emotional response (eyes lowered and shoulders dropped) this was apparently not the intended performance of the design, despite the vehicle falling slower than both a metal washer (the problem criterion) and the other design being tested. We infer that this student misinterpreted the outcome of the test as a failure, since he subsequently abandoned the design and did not incorporate any features of the design in his round 2 or 3 designs.

In this example the student did not make focused observations relevant to recognizing the lack of failure of his prototype vehicle to meet a design criterion (MFO observed absent). It is unknown if he may have predicted failure of the prototype to meet a design criterion prior to the test (APF unknown). From his emotional response to the test, we infer that he mistakenly concluded that at least one of the criteria or constraints was not met (RCC inferred present) and that he used his expectation for performance as a criterion and thus did not have a complete understanding of the criteria of the problem as (UCC inferred absent). The test that was conducted was a fair test of the problem criteria (CFT observed present), it just appeared to be misinterpreted.

Example 16: Another group of students created three variations of a vehicle in the shape of a rectangle with the four corners folded to make feet on which the vehicle rested (Fig. 3). During the round 2 building phase the students drop tested the vehicle 17 times from heights ranging from 6 to 18 inches above the tabletop (students U and V, table 7, clip 11, 3:58-7:43). In 15 of the tests the vehicle consistently landed on its feet. Twice the vehicle flipped over as it fell and each time modifications to the design were made to stabilize the fall. Students V, U, and X discussed the position of the washer, which appeared to be making the vehicle fall unevenly (clip

11, 4:14-4:30) and student V secured the washer with additional tape, possibly adjusting its position (clip 11, 4:30). In addition, a tab of masking tape was added to the top of the vehicle to facilitate a more level drop (clip 11, 6:17). When asked at the end of the activity which design fell slowest, student V identified the final design as having fallen slower than the rest of the designs. He then demonstrated a drop test of all three vehicles to the class. Each vehicle, when dropped from shoulder height rotated as it fell, landing upside down with the feet pointing upwards. Upon seeing this student V dropped his arms, sagged his shoulders, said “sad,” and turned away from the vehicles with an apparent sense of failure. Again, this student appeared to recognize design failure because the design did not behave as intended, even though the design met the criteria of the problem since the final design fell slower than the earlier designs.

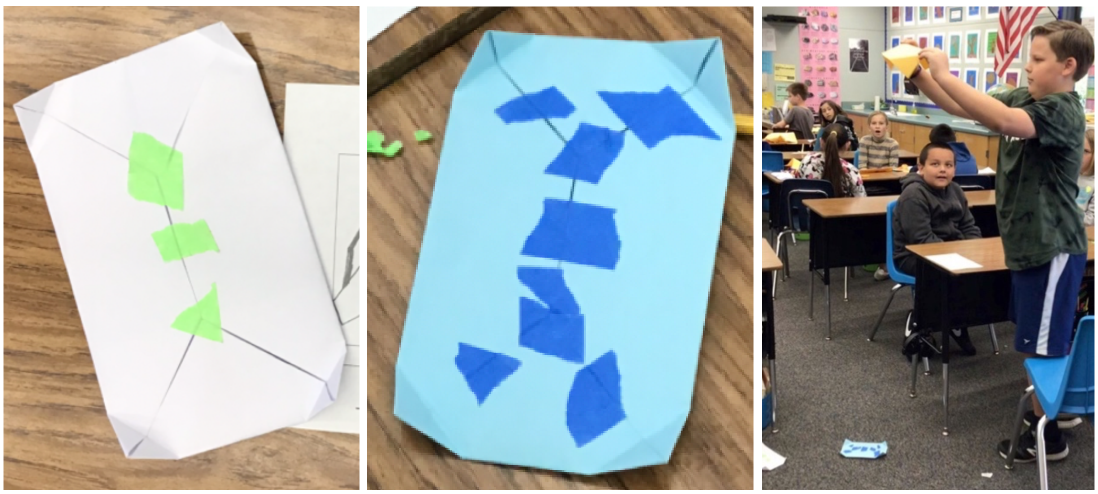

Fig. 3: Variations on a vehicle with feet. Round 1 (left), round 2 (center), and round 3 being demonstrated to the class (right – the other two vehicles are upside down on the floor).

In this example the student made focused observations relevant to recognizing the lack of failure of his prototype vehicle to meet a design criterion but chose to ignore his own statement of those observations (MFO observed present). It is unknown if he may have predicted failure of any of the prototypes to meet a design criterion prior to the test (APF unknown). From his emotional response to the demonstration, we infer that he mistakenly concluded that at least one of the criteria or constraints was not met (RCC inferred present) and that he used his expectation for performance as a criterion and thus did not have a complete understanding of the criteria of the problem (UCC inferred absent). The demonstration of the three vehicles individually dropped was not a fair test of the problem criteria (CFT observed absent).

Example 17: Student O conducts a fair drop test in which his round 1 individual design vehicle, a paper airplane, meets the criteria and constraints of the design problem by falling slower than bare metal washer when both are dropped from the same height at the same time (students O and P, table 5, clip 10, 0:22-0:30). However, student P argues with student O as to whose vehicle fell faster, which is not a criterion of the problem. P says “alright, yours fell first” (clip 10, 0:26) and O responds “no, yours fell first” (clip 10, 0:28). Each boy thinks the other boy's vehicle has failed, but O's vehicle (and we assume P's also) has met the criteria of the problem in a fair test.

In this example the student neglected to make focused observations relevant to recognizing that both of their prototype vehicles met the design criterion (MFO observed absent). It is unknown if he may have predicted failure of any of the prototypes to meet a design criterion prior to the test (APF unknown). From their debate about whose vehicle fell first, we infer that they mistakenly concluded that at least one of the criteria or constraints was not met (RCC inferred present) and that they used a criterion of falling slower than their teammates' vehicle and thus did not have a complete understanding of the criteria of the problem (UCC inferred absent). The test that was conducted was a fair test, but the results were misinterpreted according to the boys' made-up criterion (CFT observed present).

Predicted design failure

Anticipating and predicting design failure in conceptual designs and constructed prototypes is an important aspect of recognizing failure as it guides the focus on testing and observing specific features of the design.

Prediction of design failure

Example 18: Several students during the round 1 individual designs predicted a failure of their folded paper airplane design to meet the design criterion of carrying a washer (students U and V, Table 7, clip 1, 1:00-1:12; student X, table 7, clip 4, 4:56-7:41; student Q, table 5, clip 6 0:29-0:44;). As an example, student U correctly recognized and predicted such a design failure (see coded data in table 3). He explicitly called out a prediction of failure when he said "no, because the washer will just fly straight out" (clip 1, 1:05). He then focused in on a specific problem area of the design, saying "it will fly out backwards from the top" (clip 1, 1:07) and proposed a solution to remedy the problem, saying "we'll tape that part so it won't fly out" (clip 1, 1:12).

In this example student U made focused observations of aspects of the design relevant to recognizing a failure of the prototype to meet the design criterion (MFO observed present). He predicted failure of the prototypes to meet the design criterion of carrying a washer (APF observed present) and realized or acknowledged that at least one of the criteria or constraints would not be met (RCC observed present). Since in the same clip sequence he also stated that the washer will fly out when the vehicle is thrown, he did not have a complete understanding of the criteria of the problem (UCC observed absent). This example did not include any testing of a prototype (CFT not applicable).

Example 19: Two students, observing their teammate work as he did all of the prototype construction during the round 2 collaborative design, made a prediction of design failure (students K, M, and L, table 4, clip 16, 0:11-0:59):

> Watching his teammate, student L, wrap the metal washer in multiple layers of tape, student M said:
>
> > "I think that's just gonna to weigh us down"
>
> Student K agreed:
>
> > "Yeah. That's just gonna weigh us down."
>
> Student K continued saying:
>
> > "You're just literally piling tape on it."

"Why are you piling tape on it?"

Student K then connected the prediction with the criterion of the problem:

"That's literally one of those things that's going to make it fall faster."

"What are you doing? You're making it heavier."

Student L continued to put tape on the washer, apparently fixated on his design idea and not acknowledging the prediction of failure despite evidence that he heard and acknowledged the comments of his teammates (changes in facial expression and torso, head, and gaze orientation).

Student K then refined the prediction accompanied with a hand gesture indicating his prediction that the vehicle would rotate when dropped:

"It's gonna go upside down now because you put all the weight there."

He explicitly called out failure:

"It's gonna fail."

And he further refined his prediction:

"Watch, it's gonna go down in like five seconds…or two."

The test was carried out by student L and the vehicle behaved as predicted. It flipped upside down from the position it was dropped from and fell to the ground.

Student K said:

"See. See. You failed."

In this case, even though failure of the prototype to meet the design criterion was predicted and called out explicitly ("that's going to make it fall faster"), a fair test was not performed as the vehicle was not tested against a previous design. Here the student associated the movement of the vehicle (flipping upside down) with failure to meet a criterion of the design problem and he used the evidence of the vehicle flipping upside down as evidence of that design failure. In this case the students were using an incorrect conceptual model that the extra weight would make the vehicle fall faster and a correct conceptual model that the weight distribution would make it flip over. The first conceptual model and prediction were associated with the criterion of the design problem and were not what was actually tested, while the second conceptual model and prediction were associated with the designer's intended performance of the vehicle. While this intended performance of the vehicle was tested and the outcome of the test was used as evidence of design failure, the prediction, test, and conclusion could represent a misinterpreted failure of the prototype to meet the design criterion. However, student K subsequently said (clip 16, 1:35):

"The other design is better."

"This one (points to a round 1 prototype on the table)."

"The one that [student M] made."

While a fair test was not carried out, the comparison of the first design iteration in round 2 with the round 1 individual design vehicles was what was supposed to be tested (criterion 2). In this case student K demonstrated an understanding of the evolved criterion and we count this as a predicted failure of the prototype to meet the design criterion, even though a fair test was not carried out.

In this example students M and K made focused observations of aspects of the design relevant to recognizing a failure of the prototype to meet the design criterion (MFO observed present). Student K explicitly predicted failure of the prototype to meet the design criterion of falling faster (APF observed present) and realized or acknowledged that at least one of the criteria or constraints would not be met (RCC observed present). Student K also demonstrates a complete understanding of the changed criteria of the problem (UCC observed present). The test that is carried out and used as evidence is not a fair test (CFT observed absent).

Examples 20: Student S (from table 6) and student K (from table 4) erased their initial hand-drawn designs during round 1, which could indicate predicting design failure during the conceptual design phase (Figure 4). Student S's initial drawing of a paper airplane resembled a bird. This drawing was erased and replaced by a more geometrical paper airplane design that more closely resembled her constructed prototype vehicle. In this case she may have predicted that the design would fail by being too difficult of a shape to build. Student K dramatically erased his initial design of a parachute with 3 shrouds (clip 2, 1:15-1:23). He did not draw another design to replace the erased one, but he subsequently built a parachute with 4 shrouds, which could be an indication of predicted design failure during the conceptual design phase.

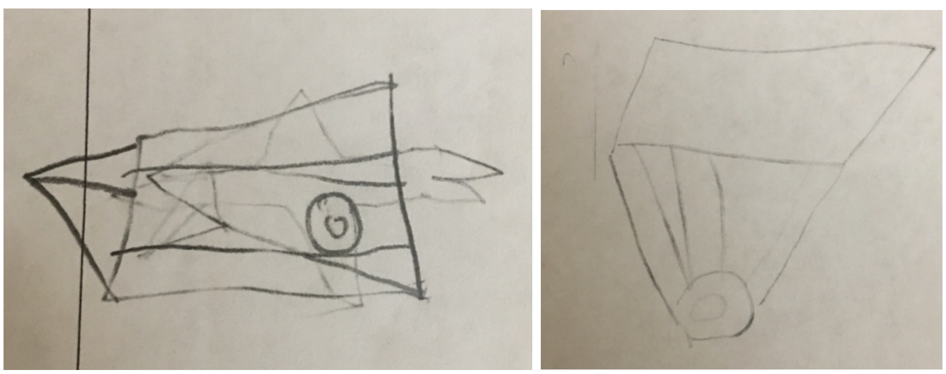

Fig. 4. Erased designs could indicate predicting design failure during the conceptual design phase. Student S (left) and student K (right).

In this example we infer from their erased drawings that students S and K made focused observations of aspects of the design relevant to recognizing a failure of the prototype to meet the design criterion (MFO inferred present), predicted failure of the prototype to meet the design criteria (APF inferred present), and realized or acknowledged that at least one of the criteria or constraints would not be met (RCC inferred present). It is unknown if either student had a complete understanding of the criteria and constraints of the problem at this point (UCC unknown). This example did not include any testing of a prototype (CFT not applicable).

Neglected or misinterpreted prediction of design failure

Since any student encountering, but not having predicted, failure of a prototype to meet a design criterion would fall into the category of neglecting to predict design failure, we do not repeat any of those cases from the examples outlined above. we did not observe any instances of misinterpreted prediction of design failure.

The ways in which design failure occurred during an engineering design challenge with fourth grade students, the type of recognition of design failure, and the observed practices that support recognizing design failure are summarized in Table 5.

Table 5
Summary of Data

<table>
<tr><th colspan="2"></th><th></th><th colspan="5">Observed practices that support recognizing design failure</th></tr>
<tr><th>Type of design failure</th><th>Type of recognition of design failure</th><th>Example #</th><th>Understanding all the criteria and constraints of the problem (UCC)</th><th>Anticipating or predicting failure in conceptual designs and/or constructed prototypes (APF)</th><th>Making focused observations during all phases of design, construction, and testing (MFO)</th><th>Conducting fair tests and accepting the results of tests as evidence (CFT)</th><th>Realizing and acknowledging that at least one of the criteria or constraints is not met (RCC)</th></tr>
<tr><td rowspan="4">Material failure</td><td rowspan="2">Correctly identified</td><td>1</td><td>unknown</td><td>present</td><td>PRESENT</td><td>n/a</td><td>present</td></tr>
<tr><td>2</td><td>present</td><td>present</td><td>PRESENT</td><td>n/a</td><td>present</td></tr>
<tr><td>Neglected (false negative identification)</td><td>-</td><td colspan="5">Not observed</td></tr>
<tr><td>Misinterpreted (false positive identification)</td><td>-</td><td colspan="5">Not observed</td></tr>
<tr><td rowspan="6">Constraint failure</td><td rowspan="3">Correctly identified</td><td>3</td><td>present</td><td>present</td><td>PRESENT</td><td>PRESENT</td><td>present</td></tr>
<tr><td>4</td><td>unknown</td><td>present</td><td>PRESENT</td><td>ABSENT</td><td>present</td></tr>
<tr><td>5</td><td>absent</td><td>PRESENT</td><td>PRESENT</td><td>ABSENT</td><td>PRESENT</td></tr>
<tr><td rowspan="2">Neglected (false negative identification)</td><td>6</td><td>absent</td><td>absent</td><td>ABSENT</td><td>ABSENT</td><td>absent</td></tr>
<tr><td>7</td><td>absent</td><td>absent</td><td>absent</td><td>ABSENT</td><td>absent</td></tr>
<tr><td>Misinterpreted (false positive identification)</td><td>-</td><td colspan="5">Not observed</td></tr>
<tr><td rowspan="10">Failure to meet design criterion</td><td rowspan="2">Correctly identified</td><td>8</td><td>present</td><td>present</td><td>PRESENT</td><td>unknown</td><td>present</td></tr>
<tr><td>9</td><td>unknown</td><td>unknown</td><td>unknown</td><td>unknown</td><td>present</td></tr>
<tr><td rowspan="5">Neglected (false negative identification)</td><td>10</td><td>ABSENT</td><td>ABSENT</td><td>ABSENT</td><td>n/a</td><td>ABSENT</td></tr>
<tr><td>11</td><td>ABSENT</td><td>absent</td><td>ABSENT</td><td>ABSENT</td><td>ABSENT</td></tr>
<tr><td>12</td><td>ABSENT</td><td>absent</td><td>ABSENT</td><td>ABSENT</td><td>ABSENT</td></tr>
<tr><td>13</td><td>ABSENT</td><td>absent</td><td>ABSENT</td><td>ABSENT</td><td>ABSENT</td></tr>
<tr><td>14</td><td>ABSENT</td><td>unknown</td><td>ABSENT</td><td>ABSENT</td><td>ABSENT</td></tr>
<tr><td rowspan="3">Misinterpreted (false positive identification)</td><td>15</td><td>absent</td><td>unknown</td><td>ABSENT</td><td>PRESENT</td><td>present*</td></tr>
<tr><td>16</td><td>absent</td><td>unknown</td><td>PRESENT</td><td>ABSENT</td><td>present*</td></tr>
<tr><td>17</td><td>absent</td><td>unknown</td><td>ABSENT</td><td>PRESENT</td><td>present*</td></tr>
<tr><td rowspan="5">Predicted design failure</td><td rowspan="3">Correctly identified</td><td>18</td><td>ABSENT</td><td>PRESENT</td><td>PRESENT</td><td>n/a</td><td>PRESENT</td></tr>
<tr><td>19</td><td>PRESENT</td><td>PRESENT</td><td>PRESENT</td><td>ABSENT</td><td>PRESENT</td></tr>
<tr><td>20</td><td>unknown</td><td>present</td><td>present</td><td>n/a</td><td>present</td></tr>
<tr><td>Neglected (false negative identification)</td><td>-</td><td colspan="5">See neglected constraint failure and neglected failure to meet design criterion</td></tr>
<tr><td>Misinterpreted (false positive identification)</td><td>-</td><td colspan="5">Not observed</td></tr>
</table>

Type of design failure, type of recognition of design failure, and observed practices that support recognizing design failure (CAPITAL/lowercase = observed/inferred).
*In cases of misinterpreted design failure, the practice of realizing and acknowledging that at least one of the criteria or constraints is not met was present but was applied to an incorrect criterion of the problem.

The data in Table 5 show that the practice of making focused observations during all phases of design, construction, and testing was present in 90% of the examples of correct recognition of design failure and absent in 90% of the examples of neglected or misinterpreted recognition of design failure. This finding is consistent with the conclusion of [7] and [8] that making focused observations during all phases of design, construction, and testing is critical to recognizing design failure.

The data in Table 5 also show that the practice of conducting fair tests and accepting the results of those tests as evidence was absent in 70% of the examples of neglected or misinterpreted recognition of design failure. This finding is consistent with the conclusion of other researchers that ignoring proper testing procedures results in neglected recognition of design failure [4], [10], [12], [13].

In addition, the data in Table 5 show that the practice of anticipating or predicting failure in conceptual designs and/or constructed prototypes was present in 90% of the examples of correct recognition of design failure and absent in at least 60% (unknown in 40%) of the examples of neglected or misinterpreted recognition of design failure. Most significantly, the practices of understanding all the criteria and constraints of the problem and realizing and acknowledging that at least one of those criteria or constraints was not met were absent in 100 % of the examples of neglected or misinterpreted recognition of design failure.

Discussion

Four types of design failure occurred during this engineering design challenge with fourth grade students: Material failure**,** constraint failure, failure of a prototype to meet a design criterion, and predicted design failure. While we did see evidence of students recognizing design failure in each of these categories, we also saw evidence of students either neglecting to recognize failure or misinterpreting design failure in some of the categories.

We also saw evidence of each of the nine categories of failure identified in Johnson *et al*. [14]. Most of the examples represented low stakes failure during private testing with ample time to take corrective action. One case (example 3) involved high stakes failure as the test of the final design was conducted in front of the class. While most of the failure events appeared to be unintended, at least one (example 4) appeared to be an intended failure with a planned test designed to demonstrate failure. While the examples of material and constraint failure were objective, the other failure events could not be characterized as objective since the appropriate criteria was not applied to the prototype tests. There were several cases (e.g., examples 15 and 17) of subjective failure in which students tested or compared their designs to other students' designs.

All five of the practices in the conceptual framework appear to support recognition of design failure. Most significantly, the practices of understanding all the criteria and constraints of the problem and realizing and acknowledging that at least one of those criteria or constraints is not met appear to be critical in supporting recognition of design failure. In cases of neglected or misinterpreted recognition of design failure there were some common issues associated with the absence of these practices:

- Students were not aware of the initial criteria and/or the changing criteria as the design challenge evolved and although some tests were conducted accurately and produced interpretable results, they did not actually test for the problem criterion (e.g., vehicles were tested by themselves instead of against a bare metal washer or a previous design).

- Students created their own criterion for the design solution (e.g., one student's vehicle fell slower than another student's vehicle).
- Students confused their expectation for performance of the prototype with the criterion for the design solution (e.g., focusing on the rotation of the falling vehicle rather than how slowly it fell).
- Tests of functionality were used as evidence of meeting or not meeting criteria (e.g., tabletop tests).
- Students did not fully understand the criteria of the problem and their intended design performance satisfied one but not all the criteria (e.g., paper airplanes fell to the ground slowly when launched, but not when dropped which was the test criterion).

While we found evidence that anticipating failure, making focused observations, and conducting fair tests were absent in cases of neglected or misinterpreted design failure, lacking an understanding and awareness of the criteria and constraints of the design problem appeared to be the largest barrier to successfully recognizing failure for the fourth-grade students we observed.

Limitations of Study

This study was exploratory in nature and was designed to identify the types of design failure encountered by fourth grade students engaged in an engineering design challenge and examine examples in which students recognized, neglected to recognize, or misinterpreted design failure. This study was limited to a sample of 24 fourth grade students and the findings are not generalizable to all engineering curricula for elementary grade levels. Additional studies are needed to further develop and test this framework with more subjects, better audio to capture more student discourse, and post-design round interviews to probe student thinking.

Implications of Study

Despite the study limitations, the finding that a lack of understanding and awareness of the criteria of the design problem represents a significant barrier to successful recognition of design failure, and thus a barrier to persisting and learning from design failure, warrants further investigation. The conceptual framework of practices supporting the recognition of design failure and the issues related to understanding and awareness of the design problem criteria can inform the development of curriculum and pedagogical strategies to support student recognition of design failure.

Conclusion

By examining how fourth grade students engaged in the practices supporting recognition of design failure as they recognized, neglected to recognize, or misinterpreted design failure during an engineering design challenge, we conclude that in addition to anticipating failure, conducting fair tests, and making focused observations, students must have an understanding and awareness of the criteria and constraints of the design problem and any changes to the criteria and/or constraints as the design challenge evolve in order to recognize design failure.

During the iterative engineering design process, each identified design failure begins a new cycle in which a new problem is defined (the problem causing the design failure), and the criteria and constraints of a new solution (the remedy for the problem) are identified. If lacking an understanding and awareness of criteria and constraints represents a barrier to recognizing an initial design failure, it also represents a barrier to recognizing all subsequent design failures in the design process and thus a barrier to persisting and learning from design failures.

This study and its conceptual framework of practices supporting the recognition of design failure will help to advance the observation and understanding of how students recognize design failure and engage in the engineering practice of persisting and learning from design failures. This understanding can inform the development of curriculum and pedagogical strategies that support productive student learning and a positive teacher view of the learning opportunities presented by engineering design failure.

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References

[1] C. M. Cunningham and G. J. Kelly, “Epistemic practices of engineering for Education,” *Science Education*, vol 101, pp. 486–505.

[2] G. Madhavan, *Applied minds: How engineers think*. WW Norton & Company, 2015.

[3] H. Petroski, *Success through failure: The paradox of design* (Vol. 92). Princeton University Press, 2006.

[4] P. S. Lottero-Perdue and E. A. Parry, "Elementary teachers’ reflections on design failures and use of fail words after teaching engineering for two years," *Journal of Pre-College Engineering Education Research,* vol. 7, 1, Article 1, pp. 1-24, 2017.

[5] D. Crismond, “Learning and using science ideas when doing investigate-and-redesign tasks: A study of naive, novice, and expert designers doing constrained and scaffolded design work,” *Journal of Research in Science Teaching*, vol. 38, 7, pp. 791-820, 2001.

[6] A. Sachs, “Stuckness' in the design studio,” *Design Studies*, vol 20, 2, pp. 195-209, 1999.

[7] D. P. Crismond, "The role of diagnostic reasoning’s role in engineering design: Case studies," in *ASEE Annual Conference and Exposition*, Pittsburgh, PA, June 22-25, 2008.

[8] D. P. Crismond and R. S. Adams, "The Informed Design Teaching and Learning Matrix," *Journal of Engineering Education,* vol. 101, no. 4, pp. 738-797, 2012.

[9] A. Jackson, A. Godwin, S. Bartholomew and N. Mentzer, “Learning from failure: A systematized review,” *International Journal of Technology and Design Education*, 1-21, 2021.

[10] P. S. Lottero-Perdue, "The engineering design process as a safe place to try again: Responses to failure by elementary teachers and students," presented at the NARST Annual International Conference, Chicago, IL, 2015.

[11] P. S. Lottero-Perdue and E. A. Parry, “Perspectives on failure in the classroom by elementary teachers new to teaching engineering,” *Journal of Pre-College Engineering Education Research*, vol. 7, 1, Article 4, pp. 1-21, 2017.

[12] C. J. Andrews, "Failure and idea evolution in an elementary engineering workshop," in *ASEE Annual Conference & Exposition*, New Orleans, LA, 2016.

[13] P. S. Lottero-Perdue and M. Tomayko, “Kindergartners’ engagement in an epistemic practice of engineering: Persisting and learning from failure,” in *ASEE Virtual Annual Conference Content Access*, June, 2020.

[14] M. Johnson, G. Kelly and C. Cunningham, “Failure and Improvement in Elementary Engineering,” *Journal of Research in STEM Education*, vol. *7,* 2, pp. 69-92, 2021.

[15] D. Harlow, R. Skinner, T. Connolly and A. Muller, “Partnering to develop a coordinated engineering education program across schools, museum field trips, and afterschool program,” *Connected Science Learning*, Vol 2, 1, pp. 1-14, 2020.

[16] Next generation science standards: For states, by states. Washington, DC: The National Academies Press. Retrieved from http://www.nextgenscience.org/.

[17] T. Anderson and J. Shattuck, “Design-based research: A decade of progress in education research?” *Educational researcher,* vol 41, 1, pp. 16-25, 2012.

[18] M. L. Castanheira, T. Crawford, C. N. Dixon, and J. L. Green, “Interactional ethnography: An approach to studying the social construction of literate practices,” *Linguistics and education*, vol 11, 4, pp. 353-400, 2000.

[19] J. J. Gumperz, “Contextualization and ideology in intercultural communication,” *Pragmatics and beyond New Series*, pp. 35-54, 2001.

[20] G. J. Kelly, “Analyzing classroom activities: Theoretical and methodological considerations,” In *Topics and trends in current science education: 9th ESERA conference selected contributions*, C. Bruguière, A. Tiberghien, and P. Clément, Eds., Dordrecht: Springer, 2014, pp. 353–368.