The Engineering Design Process as a Safe Place to Try Again: Responses to Failure by Elementary Teachers and Students

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The Engineering Design Process as a Safe Place to Try Again: Perspectives on and Responses to Failure by Elementary Teachers and Students

The addition of engineering design experiences within K-12 science education addresses the Next Generation Science Standards (NGSS Lead States, 2013), and creates intentional spaces in which students attempt to solve a problem using an engineering design process (EDP). Students are likely to experience design failure one or more times as they engineer (Cunningham & Carlsen, 2014). Design failure may be defined as follows:

> Design failure: When a designed solution, or aspect of a designed solution, does not meet criteria under constraints as specified by the problem.

Deconstructing this definition, the "designed solution" (hereafter "design") represents the attempt by the engineer to solve a problem, "criteria" are the requirements that the design must meet, and "constraints" are the limitations imposed on the designed solution. For example, an engineer may attend to the problem of designing sterile packaging for a medical syringe. Criteria likely include that the package completely seals around the syringe, is easily opened by a medical professional wearing sterile gloves, and communicates information about the syringe. Constraints may include that the packaging be under a certain cost per syringe, and of particular dimensions to be able to contain the syringe. As engineers engage in the EDP, they iteratively create and test syringe packages. These designs may fail to meet the highest standards with respect to one or more criteria or may fail to meet one or more constraints. Thus, failure to meet criteria is an expected part of the EDP. Failure is a normative condition within engineering, construed as a necessary step on the path to a successful design solution (Petroski, 2012).

While failure is a normal part of the EDP for engineers, within education, however, failure historically has had a negative connotation (e.g., failed performance on assessments, students identified as being failures) (Murphy & Meyers, 2008, Nicolaidou, M. & Ainscow, 2005). In the last decade, educational researchers, as well as the authors of the Common Core State Standards, have voiced the importance of engendering resilient responses and perseverance among students by exposing them to difficult problems and failure experiences (Dweck, 2008; Duckworth 2007; National Governors Association, 2010; Yeager & Dweck, 2012). Specifically, Dweck and colleagues' work presents two mindsets related to failure response: 1) a growth mindset, in which failures are considered growth opportunities and in which intelligence, skills and talents are regarded as mutable; and 2) a fixed mindset, in which failures are regarded as (further) evidence that one is not inherently smart or good enough, and intelligence, skills, and talents are considered to be fixed (e.g., Dweck, 2008; Yeager & Dweck, 2012).

The EDP and Opportunities to Fail and Try Again

Just as engineers engage in the EDP and generate failed – and often eventually successful – designs, students learning to engineer are likely to generate failed and successful designs as they engage in the EDP. For example, the EDP used by the Engineering is Elementary (EiE) program is depicted in Figure 1, and described in Table 1. The primary opportunities for design failure occur during designed solution testing immediately after the: Create (first design) and

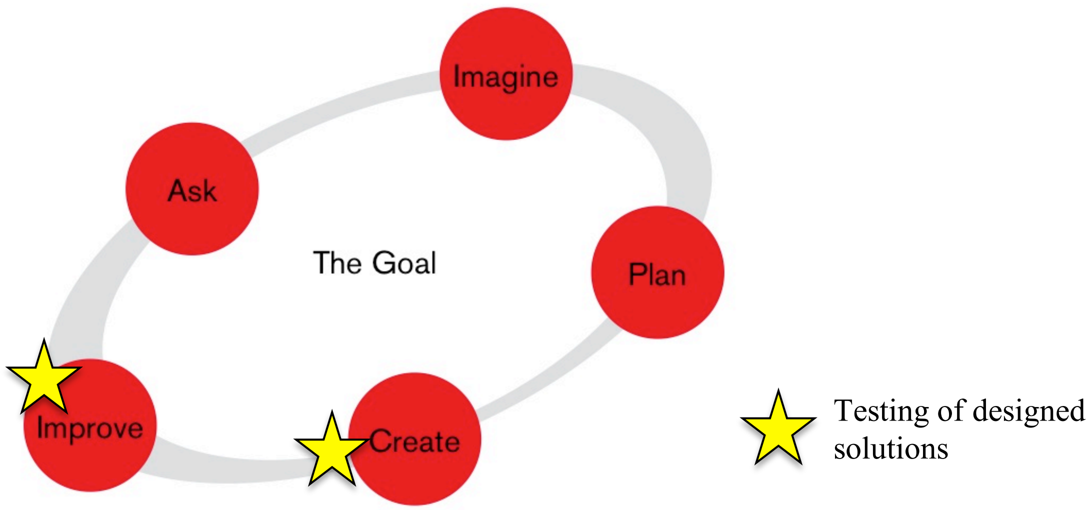

Figure 1. The EiE EDP, with designed solution testing identified with stars.

Improve (second design) steps. The EDP involves the comparison of test results to design criteria in both of these places, and the Improve step allows for iteration to re-attempt to meet those criteria or to meet them at a higher level (NRC, 2012). Certainly, the Improve step – which is indicative of enacting a growth mindset in the EDP – can be repeated to generate additional designs. Although design failure with respect to criteria is most likely to be realized after the Create and Improve steps, design failure with respect to neglecting constraints may be realized during the Plan step (e.g., ignoring budget as the design is planned).

Table 1. Engineering is Elementary EDP (EiE, 2015); design testing identified with stars.

EDP Step	Description of Step
1. Ask	• Identify the problem. • Determine design constraints • Consider relevant prior knowledge (e.g., science concepts)
2. Imagine	• Brainstorm design ideas. • Draw and label those ideas.
3. Plan	• Pick one idea. • Draw and label the idea. • Identify needed materials or conditions.
4. Create	• Carry out the plan; create the design. • Designed solution testing (and opportunity for design failure). ★
5. Improve	• Reflect on testing results. • Plan for, create, and test a new (improved) design. • Designed solution testing (and opportunity for design failure). ★

K12 Research on Failure in the EDP

While some research has examined students' engagement in engineering design, including their associated struggles and failure experiences (e.g., Fortus, 2004; Levy, 2013), there is little research that explicitly examines perspectives of failure and responses to failure among K12 teachers and students engaged in engineering design. Two recent publications have begun to address this issue. A 2014 study examined elementary teacher perspectives on failure among teachers prior to teaching an engineering unit to 3^{rd}, 4^{th}, or 5^{th} grade students. Participants included 254 survey respondents and 38 interviewees. A significant conclusion from the study was as follows:

> A largely negative view of failure (in all of its word forms) is part of the historical tradition of education and part of many teachers' personal backstories; these histories influence teachers' responses to and [lack of] use of the words fail and failure and whether/how they allow students to experience failure in the classroom. (Lottero-Perdue & Parry, 2014, pp. 29-30)

Specifically, teachers tended not to use fail words (i.e., words such as fail, failed, failure, failing) during instruction because of its negative connotation and because of their fear that students would associate a failure experience with being a failure or having a failure identity. Despite this, teachers shared that it was important for students to learn from failure, as voiced in Dweck and colleagues' work (Dweck, 2008; Yeager & Dweck, 2012).

A paper currently in press explored teachers' reports of the ways in which students responded to design failures in the classroom, and in turn, the ways in which the teachers responded to students whose designs failed (Lottero-Perdue & Parry, in press for 2015). These teachers represented a subset of the teachers in the 2014 study who had taught one or two EiE units of instruction during the 2013-2014 academic year, responded to survey questions about responses to failure (N=108), and participated in interviews (N=14).

A summary of teachers' reports of student responses to design failures is shown in Table 2 (Lottero-Perdue & Parry, in press for 2015). Note that both resilient, productive student responses and positive emotions and identities (on the left hand side of the table), and non-resilient, non-productive student responses and negative emotions and identities (on the right hand side) were included. Table 3 is a summary of the ways in which teachers reported responding to students whose designs failed, organized into three categories: 1) using general responses (i.e., offering encouragement, such as "keep it up," and asking questions); 2) employing specific interventions (i.e., encouraging students to engage in the EDP, use peers as resources, or make connections, and providing direct advice or guidance); and 3) intentionally *not* intervening, including refraining from judgment or critique.

Table 2. Teacher reports of student responses to design failure, reprinted with permission (Lottero-Perdue & Parry, in press for 2015).

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

Table 3. Teacher reports of student responses to design failure, reprinted with permission (Lottero-Perdue & Parry, in press for 2015).

Categories	Teacher Responses
General	Offering general encouragement Asking students questions
Specific Interventions	Prompting engagement in the EDP, especially the improve step: • Encouraging students to consider how to improve • Encouraging students to engage in failure analysis Encouraging students to use peers as resources: • Encouraging students to work more effectively in their teams • Encouraging students to observe others' designs Encouraging students to make connections: • Help connect design failure or next steps to real world engineering and technology • Encouraging students to reference background information Providing direct advice and guidance
Non-Interventions	Refraining from offering judgment about the success or failure of the design Refraining from intervening Offering general encouragement only when necessary

In addition to the summaries shown in Tables 2 and 3, a simple model was generated to represent the way in which students and teachers respond to design failures (Lottero-Perdue & Parry, 2015) (Figure 2). In this model, used as a starting point for the present study, design failure initially elicited some kind of initial student/team responses (#1), as described in Table 2. This may or may not elicit a teacher response (#2) – as summarized in Table 3 – to the combined design-failure-and-initial-student/team-response. The teacher response may prompt the student/team to revise their response (#3), and to perhaps even reconsider how to interpret the design failure.

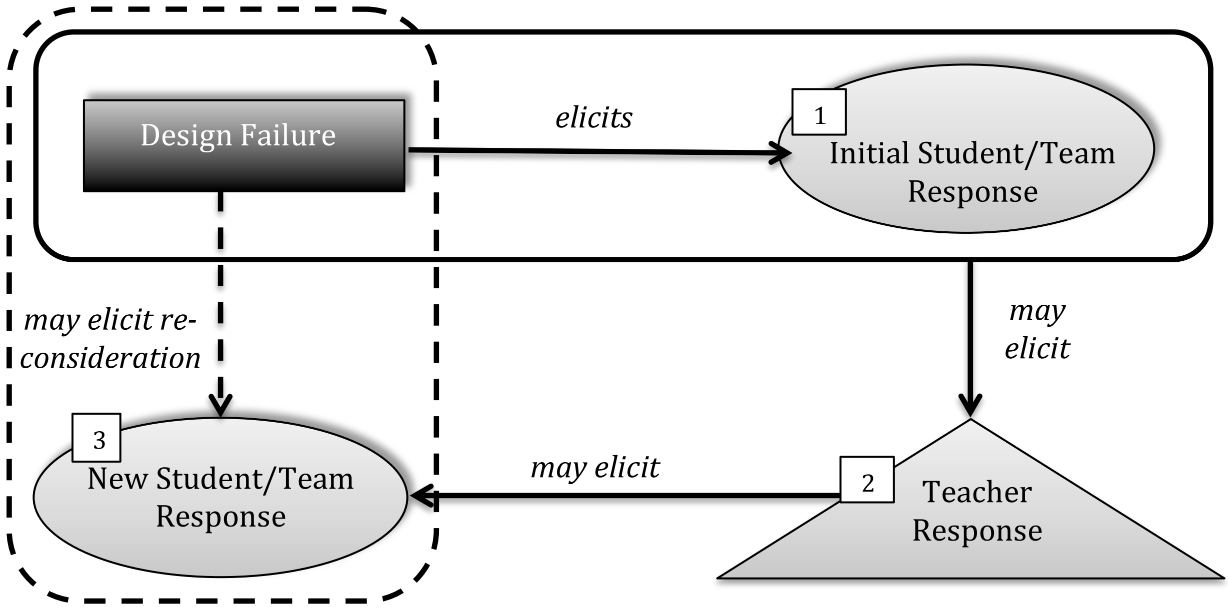

Figure 2. Model of student and teacher response to design failure, adapted with permission (Lottero-Perdue & Parry, in press for 2015).

For example, an initial team response may be to give up because a design has cleary failed and the students on the team do not know what to do next. Students may launch into blaming one another for the failed design. These are initial student/team responses to which the teacher may respond by suggesting that the team cease blaming and work together. Further, the teacher may ask some questions to initiate failure analysis – to understand how and why the design failed – and move students towards improvement. The team may then be able to reconvene, figure out the cause for failure, and begin to consider ways to improve, representing a different way to respond to the design failure than the initial student/team response (i.e., giving up and blaming).

Research Question

This paper represents a preliminary part of a larger case study, the Failure in Elementary Engineering Design (FEED) Case Study Project, in which four classrooms are examined with regard to teachers' and students' perspectives on failure, use of fail words, and responses to design failure throughout the EDP (manuscript forthcoming). Two of those four classrooms are featured here, with the primary research question guiding the present study being as follows: How do teachers and students identify and respond to design failure as they engage in the EDP?

Method

Study Context

The FEED Case Study Project is part of the Exploring the Efficacy of Elementary Engineering (E4) Project, which aims to compare student learning and engagement across two curricula: the EiE curriculum and a non-commercially available comparison curriculum.[i] The E4 Project involves multifaceted data collection efforts involving 275 3rd, 4th, and 5th grade teachers in 172 schools in the Massachusetts, Maryland and North Carolina regions, and lasting for two years (Year 1 = 2013-2014; Year 2 = 2014-2015). Prior to the first year of teaching, teachers participated in a 3-day long professional development (PD) to learn their assigned curriculum and unit, and to learn how to engage in data collection (e.g., administering pre- and post-assessments, completing logs). At the end of the first year, approximately 66% of E4 Project teachers attended a one-day, follow-up PD session that largely served to reflect upon the first year of teaching and research.

The assigned EiE unit that each teacher taught was connected to science content that they were already teaching in their classrooms. Approximately half of the EiE teachers were selected to teach an additional EiE unit of instruction, *To Get to the Other Side: Designing Bridges* (hereafter, "Bridges") prior to teaching their related science and assigned units (EiE, 2011a). Each EiE unit constitutes approximately 10 hours of instruction and culminates with a roughly 3 hour long engineering design challenge that implements the entire EDP as shown in Figure 1 and Table 1. Table 4 briefly describes the three E4 Project units that are featured in this paper.

Table 4. EiE units (2011a, 2011b, 2011c).

Unit (Unit Abbreviations in Italics)		Engineering Field	Storybook Description	Relevant Science Concepts	Students use the EDP to:
Optional Unit	Getting to the Other Side: Designing *Bridges*	Civil	A boy needs a safe footbridge so that he can get to his play fort	Balance and motion, pushes and pulls (forces)	Engineer a strong and stable bridge
Assigned Unit	A Slick Solution: Cleaning an *Oil Spill*	Environ-mental	A girl who lives in the Pacific Northwest helps to investigate an oil spill	Ecosystems, food webs, water quality testing	Engineer a process to clean up an oil spill
	Thinking Inside the Box: Designing *Plant Packages*	Packaging	A girl and boy want to safely mail a special plant to their older sister, who has moved away.	Plant parts, plant needs	Engineer a package that can keep a plant healthy for several days

As part of the E4 Project, 16 EiE and 7 comparison classrooms across these regions were selected to participate as Video Case Study (VCS) sites for intensive observation by E4 Project staff. These sites were selected to reflect a range of school demographics and units within the E4 Project; teachers selected for observation also had to be able to work with E4 Project staff to schedule observations of all lessons within each unit. Teachers were paid additional stipends for their participation as VCS site teachers. I conducted all VCS data collection efforts within Maryland, which included four EiE and one comparison curriculum classroom. Two of the EiE VCS sites are featured in this study, and described below. They were selected for analysis for this paper since both teachers taught – and were observed teaching – the *Bridges* unit in addition to their assigned units of instruction. See Figure 3 to show how the E4 Project, SEED Case Study Project, and present study related with respect to VCS sites.

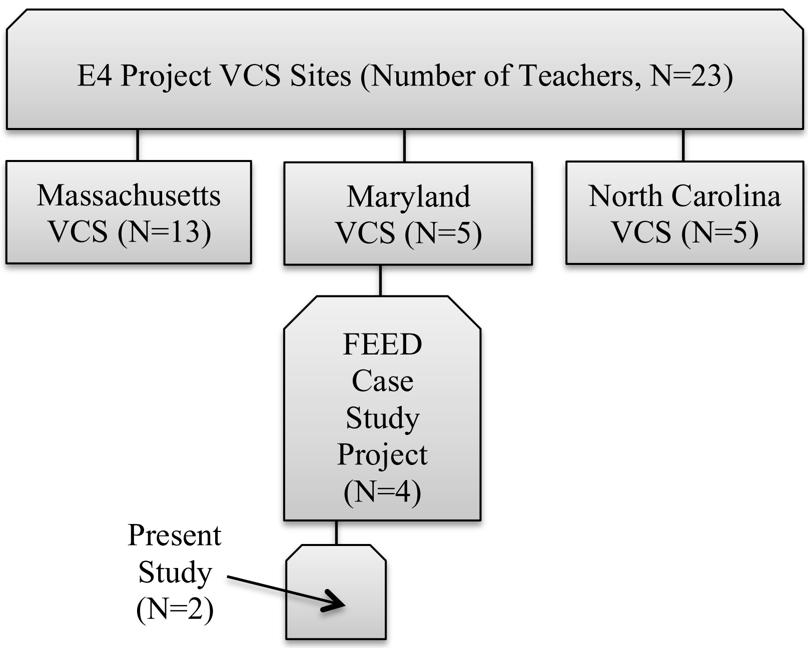

Figure 3. E4 Project, SEED Case Study Project, and present study VCS teachers.

Participants

The teachers included the present study were: Ms. Diane Darsey, who taught 4th grade at Springford Elementary; and Ms. Jessica Jarvis, who taught 3rd grade at Saint Francis Elementary, a private religious school. Both teachers are white. Prior to the study, Ms. Darsey and Ms. Jarvis had 13 and 16 years of teaching experience, respectively. Although Ms. Jarvis had taught a simple machines unit in the past with a design challenge activity, this year of this study was the first time that either teacher had taught the EDP extensively or had taught an EiE unit.

School demographics are shown in Table 5.[ii,iii] Additionally, each school has approximately 50% girls and 50% boys, and the pupil-teacher ratio in each school is between 15.6 and 16.6. Each teacher's classroom was reflective of school demographics. Ms. Darsey had

25 students in her class, and Ms. Jarvis had 29.[iv] Ms. Jarvis had a full-time aide in her classroom to help with materials management and other background assistive tasks to assist the entire class; there was one one-on-one aide to assist with one student in Ms. Darsey's class. Neither of these aides was significantly instrumental in teaching engineering to the students.

Table 5. Demographics of the schools in which Ms. Jessica Jarvis and Ms. Diane Darsey teach.

Teacher	School	Students in the FARMs Program	% of Students of Ethnicity / Race Categories						
			White	Black	Asian	Islander	Native American	Hispanic	Multiracial
Jessica Jarvis	Saint Francis	N/A (Parochial)	82%	5%	2%	2%	0%	4%	7%
Diane Darsey	Spring-ford	5%	84%	3%	4%	0%	0%	5%	4%

* FARMS = Free and Reduced Price Meals.

Both Ms. Darsey and Ms. Jarvis were selected to teach the *Bridges* unit. After the *Bridges* unit, they each taught a science unit that supported their respective assigned EiE units. For Ms. Darsey, this was an ecosystems unit; Ms. Jarvis taught about plant parts and needs. Ms. Darsey then taught the Oil Spill unit to her students (EiE, 2011), and Ms. Jarvis taught her student the Plant Packages unit (EiE, 2011).

Ms. Darsey taught her EiE units during the fall of 2013, with each EiE unit taking approximately two weeks to teach in one-hour-per day increments. An exception to this was that she spent between two and three hours on the final day of the unit as students worked through most of the engineering design challenge. Ms. Jarvis taught during the winter of 2014. Each of Ms. Jarvis's EiE units took approximately four weeks to teach, with most classroom visits lasting between 40 and 50 minutes per day. The four-week time period was interrupted with multiple snow days and school events. Similar to Ms. Darsey's approach, Ms. Jarvis allotted more time per visit– ranging from 90 minutes to 2 hours – for the engineering design challenge for the unit.

Within each of the classrooms, one team of students – a Focus Team – was selected for close observation. Being on a Focus team required that all students on the team: had parental consent for video-recording, audio-recording and interviewing; gave assent to participate as a member of the Focus Team; would be video-recorded with a camera separate from a whole-class camera (which was largely focused on the teacher); and would participate in whole-team post-unit interviews after each unit. I asked each teacher to select students in their classes who would be comfortable being closely video-recorded, and who would feel comfortable talking with the researcher. Although I did not ask for teachers to select the strongest students in their classes to participate on the Focus Team, many of the students who were selected to participate were academically strong. Each focus team in Ms. Darsey and Ms. Jarvis' classrooms was comprised of three students. Table 6 shows the Focus Teams for each classroom and each unit.

Table 6. Focus Teams in the classrooms of Ms. Diane Darsey and Ms. Jessica Jarvis.

Teacher	Unit	Focus Team Members[v]		
Ms. Diane Darsey	*Bridges*	Sophia	Margo	Connor*
	Oil Spill			
Ms. Jessica Jarvis	*Bridges*	Isabella	Grace	Ethan**
	Plant Packages			Andrew

* For the *Bridges* unit, Ms. Jarvis put students in pairs. The Sophia-Margo pair was the pair of focus for this unit; Connor was paired with another student. Connor joined Sophia and Margo for the *Oil Spill* unit, and was interviewed with Sophia Margo after both the *Bridges* and *Plants* units.
** Ethan participated on the Focus Team for the entirety of the *Bridges* unit, but did not want to be on the Focus Team for the second unit; for the Plants unit, Andrew replaced Ethan.

Data Collection and Researcher's Role – FEED Case Study Project & Present Study

The FEED Case Study Project and present study built upon existing data collection efforts that were part of the E4 Project. Table 7 shows these means of data collection, with those specifically used in the present study shown in italics. Interviews with teachers and students asked many questions beyond those referencing perspectives on and responses to failure; however, these failure questions were the focus of the FEED Case Study Project. Likewise, student journals, video data, and log notes were collected as evidence of student engagement and learning and teacher fidelity of implementation within the E4 Project; however, these data were also helpful in capturing students' design decisions and responses to design failure. The present study utilized video data, post-teaching teacher interviews, post-unit student and student journals; log data and pre-teaching teacher interviews informed FEED Case Study Project research questions about fail word use and failure perspectives not addressed here.

I collected all video and interview data and log notes for the FEED Case Study Project, and received scanned student journals for the Focus Team students from E4 Project staff. I also assisted with delivering initial PD for the E4 Project, and was the sole PD provider to deliver follow-up PD, attended by both Ms. Jarvis and Ms. Darsey. Aside from this PD or teacher-assistive role, I was positioned more as a researcher than as an ongoing PD provider while collecting data. On a few rare occasions, I left my cameras and computer (on which log notes were kept) to briefly assist with a hands-on activity.

Data Analysis

The FEED Case Study, of which the present study is a part, employed a case study approach (Yin, 2014). The major unit of analysis was the classroom, with a sub-unit of analysis being the Focus Team (see Figure 2). A full description of case and cross-case analysis for all four cases, including the two featured in the present study, within the FEED study will be described in detail in a future publication. These cases will examine, for each unit of analysis or classroom, the extent to which each teacher and her students use fail words, as well as the perspectives the teacher and students voice in interviews and project during instruction.

Table 7. FEED Case Study Project data collection; data used for present study shown in *italics*.

Data collected	Description	Timeframe
Pre-teaching Interviews with Teachers	Semi-structured, audio-recorded, in-person interviews with teachers (Spradley, 1979); approximately 20 minutes focused on perceptions about failure.	Completed approximately two weeks prior to instruction
Fidelity of Implementation Logs	Structured logs designed to assess the extent to which teachers followed the curriculum; included a place to indicate when teachers explicitly addressed failure.	Completed during instruction
Whole Class Video	One camera focused on the teacher and her interactions with students; wireless microphone worn by teacher connected to camera	
Focus Group Video	One camera focused on the Focus Team; directional or corded microphone to capture team discussions	
Focus Group Student Journals	Bound student journals, completed by students under the teacher's direction, were collected and scanned by E4 Project staff	
Post-teaching Interviews with Teachers	Semi-structured, audio-recorded, in-person interviews with teachers; approximately 20 minutes focused on failure in the context of the units taught.	Completed within two weeks after the completion of teaching the second EiE unit
Post-unit Focus Team Interview	Semi-structured, audio- and video-recorded, in-person interviews with entire focus team; approximately 20 to 30 minutes focused on engagement in the design process and perceptions of and responses to failure in the unit(s).	Completed within one week after the completion of each EiE unit

Additionally, the cases will describe how each teacher responded to students whose designs fail, and how students respond to design failure. The present study focuses exclusively on this final piece to describe design failure response episodes within Ms. Jarvis and Ms. Darsey's classrooms, and blends the findings as a cross-case analysis.

Data analysis for the present study proceeded as follows for each of the units taught by Ms. Jarvis and Ms. Darsey:

1. **Searching Video for Failure Response Episodes**: The whole class and, separately, Focus Team video files for the engineering design challenge in which the EDP was enacted, were searched for episodes in which design failures occurred or were considered, addressed by, or reflected upon by students and/or the teacher. Episodes ranged from being approximately 10 seconds to three minutes in length. In total, 63 episodes were identified within Jessica Jarvis's classroom, and 78 were identified within Diane Darsey's classroom.
2. **Coding Video Failure Response Episodes**: Episodes were captured as video segments within Studiocode© and coded as involving a(n): teacher-student interaction within a small group/team setting (N = 13 Darsey, N = 20 Jarvis); teacher-student interaction within a whole-class discussion (N = 41 Darsey, N = 18 Jarvis); student-student interaction within a group/team setting (N = 22 Darsey, N = 24 Jarvis); student-student interaction within a whole-class discussion (N = 0, both teachers); or, less often, exchange between the teacher and researcher (N = 1 Jarvis) or between the researcher and students (N = 2 Darsey).
3. **Labeling or Sub-coding Video Failure Response Episodes**: Episodes were labeled or sub-coded using a total of 22 sub-codes: 2 indicated if the response to design failure was by the teacher or student(s); 17 came from the aforementioned previous work on student and teacher responses to failure (see Tables 2 and 3; e.g., failure analysis, negative team interaction); and 3 emerged during the video analysis. In this way, sub-codes represented a "combination of emerging and pre-determined codes" (Creswell, 2014, p. 199).
4. **Summarizing and Transcribing Video Failure Response Episodes**: Each coded episode was summarized and transcribed verbatim by the author, and a document for each case/teacher containing all coded Failure Response Episodes was generated.
5. **Re-coding and Constructing Themes to Describe the Video Data**: Once video failure episodes had been transcribed, each video episode was iteratively read and re-read to ensure that the codes and sub-codes accurately reflected the nature of student and/or teacher responses to failure. Once the coding process was complete, themes related to student and teacher response to design failure were constructed (Glaser & Strauss, 1967). As was the case for sub-codes, these themes both reinforced and expanded current understandings from the literature about student and teacher responses to design failure.
6. **Connecting Video Data Themes to Ideas within Other Data Sources:** As themes were constructed from video data analysis, they were checked against interview and student journal data to identify ways in which the themes were supported, enhanced, or refuted by those additional sources.

In what follows, I describe cross-case findings as a result of this analysis. The findings section provides insight into four themes with respect to the failure response data, and the conclusions section summarizes these findings and presents a revised model of how students and teachers respond to design failure.

Findings

Although there were differences in approaches between Ms. Darsey and Ms. Jarvis, those differences will not be significantly explored in this paper. Case descriptions, including the fail word use, perspectives on failure, and responses to student failure for Ms. Darsey, Ms. Jarvis and two other teachers will be elaborated in future publications from the FEED Case Study Project. In short, it is accurate to characterize Ms. Darsey as a teacher who tends not to intervene or provide direct advice as students work through the EDP and when students' designs fail (Video data, Pre- and Post-Teaching Interview data). She describes herself as someone who is not "warm and fuzzy" and emphasizes the need for students to be problem solvers and figure things out on their own (Post Teaching Interview). Ms. Jarvis seems to have a broader array of responses to students whose designs fail (Video Data), ranging from intentional non-intervention to delivering very direct suggestions about why designs failed and how to improve them (Video Data, Post Teaching Interview). This section emphasizes four cross-case findings from the analysis: 1) resilient, positive or productive student responses to design failure; 2) non-resilient, negative or non-productive student responses to design failure; 3) teacher responses to students' design failures; and 4) student and teacher anticipations of design failure as pre-emptive responses to failure.

Resilient, Positive or Productive Student Responses to Design Failure

To begin the analysis of student responses to design failure within Ms. Darsey's and Ms. Jarvis's classrooms, I searched for student actions and emotions that emerged from teachers' reports of student responses to design failures (Lottero-Perdue & Parry, in press for 2015). Note that the data being analyzed for the present study included video data from: 1) one whole class camera that followed the teacher and her exchanges with students in whole class and small group work settings; and 2) another Focus Team camera that was fixed on this team throughout the EiE units. At times, the camera could capture interactions within and among teams other than the Focus Team, but largely, student responses were most evident within the Focus Team video.

The resilient, productive student responses to design failure observed in the video data for more than one episode across the two classrooms are shown in Table 8 and include:

- Engaging in failure analysis, which includes both identifying ways in which the design failed and considering why it failed;
- Focusing on improvement, in which a response to design failure includes a relatively immediate consideration by students of what can be done to improve the design (this occurs prior to moving into the Improve step of the EDP);
- Expressing a positive emotion in response to the design failure (not in response to the way in which the design was successful); and
- Referencing background science or engineering information that helps students understand why the design failed or how best to improve it

Other possible productive student responses (e.g., seeking help from peers in other groups) were not observed in the student discourse, or were difficult to observe (e.g., not enacting a failure identity). However, this does not mean to suggest that these did not occur; rather, they were not captured in the video data.

Table 8. Resilient, productive student responses to design failure observed in the video data.

	Number of Failure Response Episodes							
	Diane Darsey's Classroom (N = 78)				Jessica Jarvis's Classroom (N = 63)			
	Bridges		*Oil Spill*		*Bridges*		*Plant Packages*	
	Focus Team	Other Students	Focus Team	Other Students	Focus Team	Other Students	Focus Team	Other Students
Engaging in Failure Analysis	2	4	8	5	2	2	14	9
Focusing on Improvement	1	2	6	4	0	1	11	4
Expressing Positive Emotion	0	4	1	0	3	0	0	0
Referencing Background Information	0	0	0	0	0	0	4	0

An example of the way in which students engaged in some of these positive responses to design failure is from the Focus Team in Jessica Jarvis's classroom. In this case, Isabella, Andrew and Grace were trying to make sense of their testing results from their first plant package design. In this engineering challenge, students had to design a package for a plant that met a variety of functions, including: that it could keep the plant healthy (as measured on a plant health rubric designed with student input) for three to four days on a shelf without additional watering, and that the package could communicate the plant needs and how the package should be carried. Isabella, Andrew, and Grace had created a package out of a 2L bottle. The top of the bottle had be cut from the bottom and then flipped over, and the plant sat inside the inverted top. The mouth of the bottle sat into the bottle's bottom in which there was a pool of water; the team had stuffed cotton balls into the mouth to enable water to move from the pool upwards to the plant to keep the plant hydrated (see Figure 4, Andrew's idea, for an approximate sketch of this plan). The team covered the package with plastic wrap into which they had created a few holes.

Isabella, Andrew and Grace received their package after a four-day period. The following exchange occurred:

> Isabella: Oh, I love this.
> Andrew: Wait just a minute.
> Isabella: It's doin' - it's doin' good. Look at that. That's good.
> Andrew: Half of - half of the leaves on that plant are dead.
> Isabella: [squints her eyes at Andrew, annoyed] It's because it was in for another day.*
> Grace: I think we should do it without the plastic wrap and without the cotton balls.
> Andrew: Then what would we use?
> (Focus Team Video)
>
> **Three instead of four days due to a snow day.*

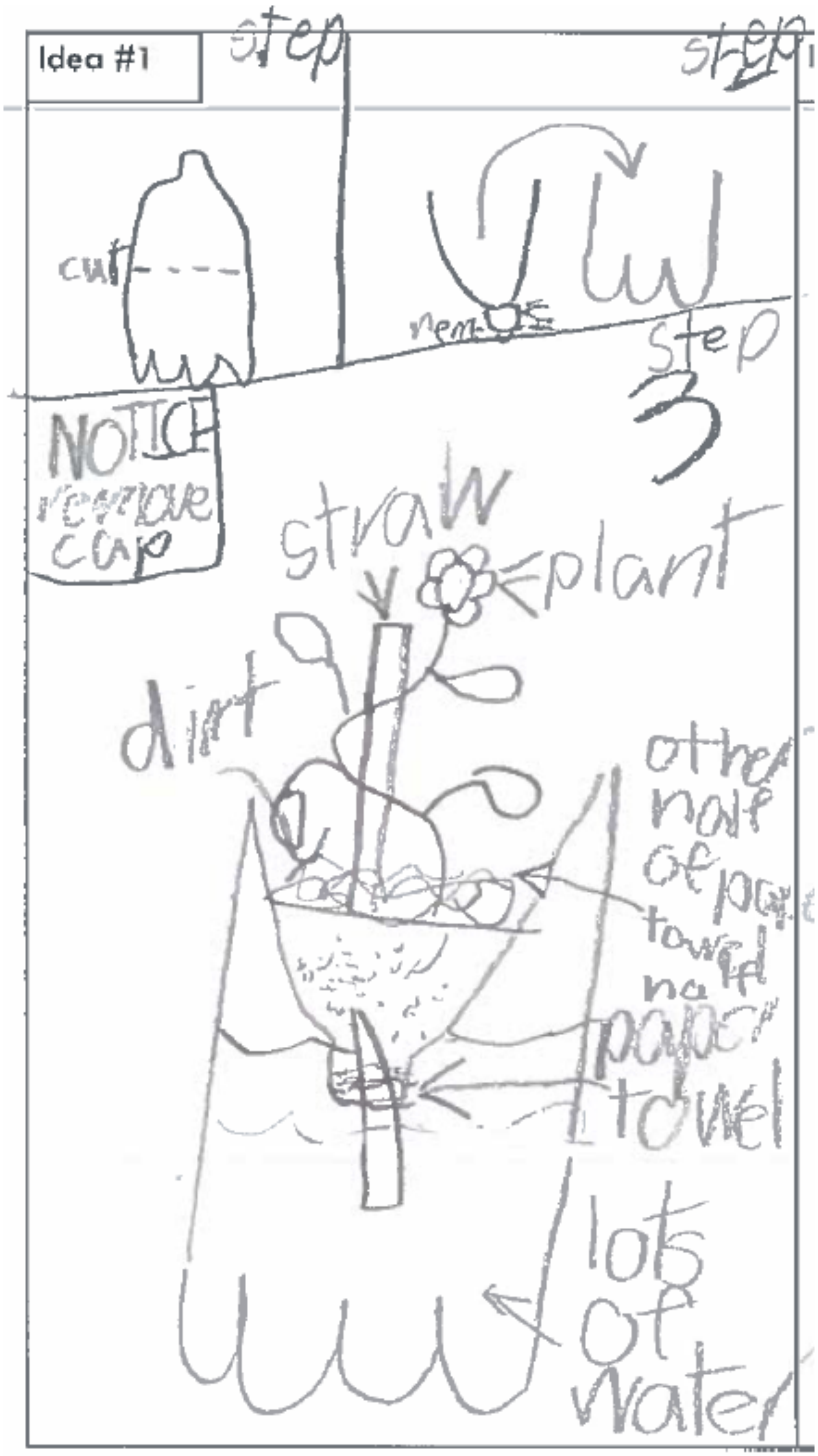

Figure 4. Andrew's idea for the plant package design, which shows bottle construction.

Note: Andrew's idea was different from the team's first design plan in that Andrew's idea: 1) does not show that the team's first design included covering the top of the package with plastic wrap; and 2) shows paper towel as a wick, rather than cotton balls used for a wick in the team's first design. Andrew's idea does represent the team's second design. (Andrew's Student Journal)

Although Isabella was hopeful, Andrew noticed that the leaves do not look healthy. Right away, and without teacher intervention, they began to simultaneously think about failure analysis (perhaps the plastic wrap that covered the top part of the plant was to blame) and improvement (perhaps next time, no plastic wrap). They discussed this further:

> Ms. Jarvis: [to whole class, in background] Take the plant out so you can really look at it.
> Isabella: Can we take the plant out? Good.
> Andrew: And find the problem.
> Isabella: What?
> Andrew: The - that suffocated [pointing to the plastic wrap].
> Isabella: That's not suffocated, it has holes. / I think this time -
> Grace: Plus, there's an opening right here.
> Isabella: What?
> Grace: There's a big opening.
> Andrew: So it's not that.
> Isabella: Yeah, there's a bit opening so it's not suffocated.
> Andrew: That - a lack of water.
> Grace: Guys, let's just take our plant out! [over-talking with Isabella, below]
> Isabella: 'Cuz the cotton ball - [over-talking with Grace, above]
> Andrew: Is it lack of water?
> Isabella: Because the cotton ball's still there. No the cotton ball is still sucking things up.
> Andrew: Then what's the problem?
> Isabella: I don't know.
> Andrew: Lack of water.
> Isabella: No. [puts finger in soil] Nope, not lack of water.
> Andrew: [puts finger in soil]
> Isabella: The soil is as wet as could be.
> Andrew: You guys were telling me to add more water. So maybe it's too much water.
> Isabella: I think. I think it had just the right amount, because I - but then -
> Grace: Andrew was right -
> Andrew: I told you.
> Grace: - it had too much water.
> Isabella: Yeah. Because I did say it had so - it was so wet. It needs a lot less water [over-talking with Andrew]
> Andrew: [over-talking a couple words, inaudible] Or if we took off the plastic wrap, then the water would go up [raising his hand high] and out and then it could evaporate.
> Isabella: Oh, yeah. This time, let's leave off the plastic wrap.
> Andrew: No plastic wrap! …
> Isabella: No plastic wrap.
> (Focus Team Video)

Notice that the team works together to determine that the leaves' brown and unhealthy nature are not due to under-watering, but perhaps due to too much water staying in the soil. Andrew connects this to prior learning (background knowledge) about the water cycle. Ultimately, the team ultimately used the idea shown in Figure 4, which included a paper towel wick and no plastic wrap. The plant was more healthy as a result.

In Post-unit Focus Team Interviews, Isabella, Andrew, and Grace recalled this process of figuring out what was the cause of the unhealthy leaves (failure analysis) and how to prevent this problem in their subsequent design improvement. Failure analysis and improvement were also embedded in the Focus Teams' design process storylines for the Bridges unit in Jessica Jarvis's classroom (for Isabella, Ethan, and Grace), and for the Bridges and Oil Spill units for Diane Darsey's classroom (for Connor, Sophia, and Margo).

Post-teaching Teacher Interviews offered some additional insight into resilient and productive responses to design failure. In her interview, Diane did not recall any students being too disappointed with the Oil Spill challenge, recalling: "there wasn't any team member that got disgruntled or got upset or cried or was very forceful" (Post Teaching Interview). She mentioned that students were more frustrated by the Bridges unit, discussed in the next section. Jessica shared a similar sentiment with regard to the Bridges unit being more frustrating and in that "most of them were okay with it" when their designs failed. She elaborated, "They knew they were going to have a chance to improve. I don't think anyone got too discouraged." This chance to try again was also evident in an episode in which Isabella reminds her teammates "remember, we do have a second chance, and we're running out of time" (Focus Team Video).

Non-Resilient, Negative or Non-Productive Student Responses to Design Failure

As suggested above, students in Diane Darsey's and Jessica Jarvis's classrooms had some non-resilient, negative and non-productive student responses to design failures, including negative emotions like frustration or disappointment. In her Post-teaching Interview, for example, Diane recalled some frustration among her students with regard to the Bridges unit, where the designed solution was a more open-ended task and where students did not meet success as often as in the Oil Spill unit, in which she only recalled one team becoming frustrated. Diane also sensed that students in her classroom were overly competitive for the Bridges unit, but thought that competition decreased for the Oil Spill unit. For her population of largely affluent students, Diane said, "competition is pretty much in-bred." Jessica was frustrated by negative team dynamics, such as "the blaming that goes on" when designs do not work as planned (Post-teaching Interview). Also, both Jessica (as evident from Whole Class Video) and Diane (articulated in the Post-teaching interview), had cases in which students seemed to disengage and give up, lose interest, and disengage when designs fail. Diane shared that one group of students got "bored with the task when it became difficult for them," and then quickly came up with a new design without much thinking – another non-productive response mentioned in the Lottero-Perdue & Parry (in press for 2015) study and in Table 2. Diane elaborated that she sees this often in mathematics instruction when students "do not have the tenacity to stay with the task" (Post-teaching interview). These student responses – expressing negative emotions, engaging in negative team dynamics, and giving up or disengaging – were evident within two or more whole class and/or Focus Team video episodes (see Table 9).

The most frequent non-productive response by students, however, was "Ignoring Background Information" (Table 9). This original category of non-resilient, non-productive responses to design failure – as expressed in Lottero-Perdue & Parry (in press for 2015) – was intended to capture instances in which, for example, students ignored the need for a plant to

Table 9. Non-resilient, negative or non-productive student responses to design failure observed in the video data.

	Number of Failure Response Episodes							
	Diane Darsey's Classroom (N = 78)				Jessica Jarvis's Classroom (N = 63)			
	Bridges		*Oil Spill*		*Bridges*		*Plants*	
	Focus Team	Other Students	Focus Team	Other Students	Focus Team	Other Students	Focus Team	Other Students
Ignoring Background Information, i.e. Testing Procedures	5	0	8	0	2	0	1	2
Expressing Negative Emotion	0	1	2	0	2	0	0	2
Engaging in Negative Team Dynamics	0	0	0	0	1	1	0	2
Giving Up or Losing Interest	0	0	0	0	0	0	2	0

receive plenty of sunlight when they designed their plant package. However, more often what was being ignored by students was proper testing procedures. Ignoring these procedures tended to invalidate testing results, seemingly unbeknownst to students, and – in all the cases observed here – suggested that the design had been more successful than was actually the case. As suggested in Table 9, evidence from Focus Team and whole class video indicated that this occurred across both teachers and all three units.

An example of ignoring testing procedures is from the Oil Spill unit in Diane Darsey's class. Students were charged in this challenge with designing an oil spill clean-up process using simple materials (e.g., cotton balls, yarn, etc.) in various combinations and in a specific order to contain and then absorb the oil. The oil they were to clean had been deposited on a model shoreline. The model used was an 8" x 8" square aluminum pan in which about one third of the pan has a sloped shoreline made of gravel, and the rest of the pan was filled with water. The teacher deposited approximately ½ Tablespoon (7.4 ml) of black-dyed vegetable oil on the surface of the water, and teams enacted their oil spill clean-up processes that they designed. To test the extent to which the process was successful, each team was supposed to: 1) use a strip of paper bag paper to press along the shore and shoreline to see if any oil has gotten onto the shore (Shore Oil Detection Test); and 2) press a rectangular piece of 12-block grid paper onto the water's surface to see what amount of oil remains on the surface of the water (Water Oil Detection Test).[vi] For an accurate Shore Score test, the paper bag strip must be pressed where the water meets the shoreline. For an accurate Environmental Impact Score, the entire grid paper must touch the water along its surface, being entirely wet and likely spotted with oil upon its removal.

The Focus Team in Diane Darsey's class engaged in the Oil Spill unit consisted of Margo, Sophia and Connor. In class, they shared with me that they did well on the Water Oil Detection Test for their first oil spill clean up design, receiving a rather low score of 6 points; lower scores are better for the oil spill challenge, and represent less oil present in the environment after clean up. However, I noticed that their grid paper was not entirely wet, and thus, not dipped entirely into the water to measure all of the oil present in the water:

> Margo: [to Pam] We did pretty well. We got 6 points for all that [pointing to paper used in the ecosystem score]
> Pam: What - what about this side? [points to dry half of ecosystem score paper]
> Margo: There was nothing.
> Sophia: Nothing.
> Pam: There was nothing on that side?
> Margo: Yeah, it didn't - it didn't look like there was anything on that side. Did there?
> Sophia: No.
> Margo: No.
> Pam: No, I didn't know if it was wet. It wasn't wet at all, right? [Pam is touching the paper, confirming that half of it is dry]
> Sophia: No, all of - all of -
> Margo: I, like, hold it there for, like, 5 seconds.
> Sophia: Yeah, because that's when we took it off, all of it, like, together.
> Pam: Got it.
> (Focus Team Video)

In my role as a researcher, I did not push the issue with the team, but later shared with Ms. Darsey that she may need to review the Water Oil Detection Test procedures. The Focus Team ultimately kept the 6-point (invalid) score, and did not see it as problematic. The difficulty here is that in actuality – if complete success is a score of zero (no oil) and complete failure is a score of 36 – they have interpreted their design as being less of a failure or more of a success than it truly is, disabling them from conducting a meaningful failure analysis and subsequent improvement informed by valid testing results.

Later, around the time that teams were testing their second oil-spill clean-up design, two things co-occurred: 1) the Focus Team was testing their second design, and 2) Ms. Darsey was reminding the whole class that teams must dip the entire grid in the water to get an accurate result for the Water Oil Detection Test. Yet again, a large portion of the Focus Team's grid was dry, as is clear on the video. Note the shift in the team's testing procedures – and the resulting difference in outcome – in the episode, below, where bold represents what the team is doing in the midst of Ms. Darsey's whole-class discussion:

> Ms. Darsey: [in background to whole class] Also, on the oil indicator, when you dip your oil indicator, you had, you had to make sure that all of your grid - that you had a chance to get all of your grid wet.
> **Margo: [ignoring Ms. Darsey, to Sophia, whispering] One, two, 3 points.**
> **Connor: [whispering to Margo and Sophia] Good. Good, good, good.**
> Ms. Darsey: Does that make sense? Some of you just dipped it in the corner, and when I pulled it out, or when you pulled it out, you only had three boxes wet.

> **Sophia: [whispering to Margo, smiling] We got 5 points [total]!**
> Ms. Darsey: Does that tell you anything about the dry area that didn't make contact with the water?
> Multiple students in classroom: [some indicate no]
> Ms. Darsey: Does that make sense?
> Connor: [to Sophia and Margo, whispering] Hey guys. [they ignore him]
> Ms. Darsey: Like this one - let me see this one. See this one is done correctly.
> **[Sophia and Margo now pay attention to Ms. Darsey. Hearing what she's saying, they look at one another and them move to repeat their oil detection test]**
> Ms. Darsey: If you notice, it's all wet - all the grids are wet.
> Okay, and you can see there was a lot of oil. Some people only dipped it so that the top three were wet and all this was still dry. Does that give you a valid result?
> Multiple students in classroom: [some indicate no]
> Ms. Darsey: Does that give you a valid result?
> Multiple students in classroom: [some indicate no]
> Ms. Darsey: No, because all the oil that would be over here [pointing to where the dry spot would be] you didn't get a chance to put the paper on ad see if it was existing.
> **[Margo pulls out the now wet oil detection paper, turning it over, large oil spots are evident]**
> Ms. Darsey: Does that make sense?
> **[Afterwards, Margo and Sophia determine that they have gotten a score of 15]**
> (Focus Team Video)

This time, the end result is that the team had a more accurate score, yet without Ms. Darsey's guidance, the team would have continued to have an incorrect score. Although this is a better outcome, since the first design was tested improperly, it was difficult to get a true comparison of the first and second design results for this Focus Team's oil spill clean up process.

This is one example of inaccurate testing procedures in the Oil Spill unit, another example being how the materials were used to clean up. The materials were to be used in particular ways, e.g., the spoon had a "per dip" cost that was often not accounted for by teams when they calculated their total clean-up cost. Diane reflected on this in her Post-teaching interview:

> I feel like everybody was successful in the Oil Spill unit, but I think that a part of them being successful was, like, not overseeing them tightly enough with the utilization of their tools. You know, like you said, the one kid- they kept scooping and scooping [without accounting for that in their budget.] (Diane Darsey, Post-teaching Interview)

The Focus Team in Diane Darsey's class did not specifically mention the issue of the dry oil detection paper in their Post-unit Interview, and when asked, all shared that their first design score was accurate. Connor stated in the interview that part of the reason for their more poorly performing second oil spill clean-up design was that "she [Ms. Darsey] changed the rule [about how many dips per materials were allowed] for the second one." Later in the interview, Margo said, "She changed the rule. We could've, we could've used it more times if she hadn't changed the rule. I don't think it's fair that she didn't tell us … because then we would have gotten a better improvement."

Similar inconsistencies in the testing process were evident in the Bridges unit, where teams placed the bridge load (a cup of steel hex nuts) sometimes directly on a pier and other times in the center of the widest span, the latter of which was the intent of the curriculum, although not clear to either teacher. Also, plant packages were evaluated by the student teams themselves for package functions such as their ability to communicate the needs of the plant inside. However, teams did not always evaluate these correctly, as Jessica mentioned in her Post-Teaching Interview: "That was the only thing. They evaluate themselves, so how accurate those evaluations are, because that one team yesterday for communicate, gave themselves a perfect score, but there was no communication evident."[vii]

Teacher Responses to Student Design Failures

Ms. Jarvis and Ms. Darsey responded to student design failure in a range of ways largely consistent with the responses summarized in Table 3. Table 10 includes the teacher response categories present within one or more failure response episodes in which the teachers interacted with the whole class or a small group of students. Teachers offered general encouragement such as, "you can do it!" (Jessica, Whole Class Video). Both teachers asked many questions of teams

Table 10. Teacher responses to student design failures from Lottero-Perdue & Parry (in press for 2015) or new from the present analysis (indicated with *).

Teacher Response Categories		Number of Failure Response Episodes involving Teacher	
		Diane Darsey's Classroom (N = 54)	Jessica Jarvis's Classroom (N = 38)
General	Offering general encouragement	3	4
	Asking students questions	41	24
Specific	Encouraging students to consider how to improve	23	16
	Encouraging students to engage in failure analysis	18	7
	Encouraging students to work more effectively in their teams	0	4
	Encouraging students to observe others' designs	0	1
	Connecting design failure to real world engineering	3	1
	Encouraging students to reference background information	0	3
	Providing direct advice or guidance	1	7
	Offering judgment about the success or failure of the design*	5	4
	Reminding students about testing procedures, constraints or criteria*	15	4

and students, ranging from very broad questions (e.g., from Jessica, “So what are you working on improving?”) to very specific questions (e.g., from Diane, “Is that [bridge] going to be stable?”). Jessica shared in her Post-teaching interview that “the best way to do it [respond to students during the design process] is just through questioning the kid … like ‘How can you do this? … How are you going to reduce that? Do you really need that?’ That kind of thing.”

Teachers offered more specific responses to design failures, as shown in Table 10. For example, many teacher responses are evident in the following episode:

> Ms. Jarvis: So talk together and see what you're going to do. You guys need more supports under your bridge. Did you use arches at all?
> Tiffany: Yes.
> Ms. Jarvis: You did? Did you use columns?
> Tiffany: We did, but - we tried and it didn't really work. We tried but it didn't really work.
> Ms. Jarvis: Okay, what did you make your arch out of?
> Tiffany: Paper
> Ms. Jarvis: Just like regular paper, Jenny-ps?
> Tiffany: Mmm hmm, yeah.
> Ms. Jarvis: How can you make your paper stronger so that it pushes up more?
> Tiffany: We could use index cards or put straws underneath.
> Ms. Jarvis: Okay. Or use index cards.
> Tiffany: Make it stronger.
> Ms. Jarvis: Make it stronger. Did you fold your paper?
> Tiffany: [inaudible, affirmative]
> Ms. Jarvis: You did? Okay. Can you attach your arch to your span somehow?
> (Whole Class Video)

In this episode, Ms. Jarvis encourages students to consider why their bridge failed (failure analysis) and how they can improve it for the second design. She also encourages the team members of this team to talk to one another, as their communication had been lacking (evident in a previous episode). Perhaps because the team was struggling so much, she used very specific questions to direct them towards an improved design.

Another broad category of teacher responses included in Table 3 was “non-interventions” such as trying not to judge the success or failure of students’ work, refraining from intervening, and offering encouragement only when necessary. These non-interventions were difficult to capture using video analysis, since they largely involve what the teacher is not doing. Certainly, teachers: had to rely on students to self evaluate, as Jessica mentioned in the previous section; did not intervene directly in both designs for every team; and did not tend to offer praise and encouragement to the extreme. Perhaps more telling with respect to non-intervention are the teachers’ perspectives shared in the Post-teaching Interviews. Diane shared that she “was very cognizant about not giving them a lot of suggestions. I’m letting them find their way.” (Post-Teaching Interview). This is consistent with her Pre-teaching Interview perspectives on students taking responsibility for their own learning. Also, Jessica shared, “It’s hard to be present to everyone and sometimes when you are present, it’s not a good point to intervene. Sometimes you need to know when to be quiet and to let them sort things out on their own” (Post-Teaching Interview).

Perhaps most interesting from this study were the teacher responses to student design failures *not* captured in the aforementioned study. Those are indicated with an asterisk in Table 10 and are: 1) offering judgment about the success or failure of the design, and 2) reminding students about testing procedures. The first of these involves the teachers helping students with the first part of failure analysis: identifying when failure occurred. Students may not recognize that failure has occurred without clarity and guidance from the teacher. This may involve the teacher not simply judging, but also modeling the evaluation process for students. This occurred when a team incorrectly performed the Shore Oil Detection Test and asserted that their shore was oil-free, then Ms. Darsey re-performed the test, showing that there was indeed oil on the shore. Teacher judgment about design failure was also evident in the following exchange in Ms. Jarvis's classroom in which Ms. Jarvis identified that a team had incorrectly assessed their package to be a perfect communicator when in reality, the package did not communicate about plant care at all; note that she employed the help of other students to help make this judgment:

> Mrs. Jarvis: Does it communicate?
> Students from the classroom: No / not really. [a few students from the audience]
> Student from the classroom: Well, it just says carry.
> Mrs. Jarvis: That tells how to carry, but does it tell the needs of the plant?
> Two students from the team, simultaneously: No.
> Ms. Jarvis: ... [identifies a student in the audience] You have your rubric open. What does it say for communicate?
> Another student from the class: It doesn't really display.
> Another student, called on by Ms. Jarvis: It says how it's supposed to communicate how to care for the plant.
> Ms. Jarvis: Does it tell how to care for the plant?
> Student from team: No.
> Ms. Jarvis: [in a playful voice] Uh oh! So you would have to add that. Okay.
> (Whole Class Video)

As mentioned previously, self evaluation by students can be problematic, especially if testing procedures are unclear. Likewise, evaluation without oversight could result in invalid results and, thus, an inability to engage in failure analysis and subsequent improvement. Related to this point, and as exemplified earlier when Ms. Darsey described the importance of dipping the entire paper grid in the water for the Water Oil Detection test, teachers had to remind students about proper testing procedures and constraints. This was largely in response to what were likely design failures that were not interpreted as such by student teams.

Anticipating Failure: Trying Again

Another theme that emerged from the analysis that expanded the survey and interview-based findings from the Lottero-Perdue & Parry (in press for 2015) study was that teacher and student responses to failure began *prior to* design failure experiences. These responses may be regarded as anticipations of failure or preparations for failure. Prior to having a design failure experience Ms. Darsey (3 episodes) and Ms. Jarvis (5 episodes) forewarned students in a general way that design failure was possible. This is evident in the following exchange:

> Ms. Jarvis: You may fail, and you know what? It's okay [emphasis on okay]. You are going to have the chance to improve it next week. So, don't get discouraged. Do you think / engineers always have success?
> Multiple students: No.
> Ms. Jarvis: This is real. As my son would say, the struggle is real. (Laughs)
> (Whole Class Video)

Students also anticipated and were concerned about failure (2 episodes in Ms. Jarvis's classroom), for example when Grace whispered to her teammates, "Please don't let us fail," after a previous warning from Ms. Jarvis to the class that "you may fail." Conversely, students tended to anticipate that they would be successful in the design process (4 episodes in Ms. Jarvis's classroom; 1 in Ms. Darsey's). For example, Isabella excitedly shared the following about her plant package: "This is going to work out perfectly!" (Whole Class Video, Ms. Jarvis's classroom). Additionally, one episode from each class anticipated a more balanced view of success and failure, anticipating design failure with respect to some aspects of the design, and success with respect to others.

The teachers not only provided general forewarnings about the possibility of failure they also anticipated failure specific to students' designs (1 episode each, Darsey and Jarvis). This was the case in the following exchange between Ms. Darsey and a team that was constructing a bridge that was much higher than it needed to be and precariously balanced on top of the abutments:

> Ms. Darsey: Is that going to stable?
> Girl: No.
> Boy: No.
> Ms. Darsey: Is that going to be strong?
> Girl: No.
> Boy: No.
> Birl: I'm still working on that.
> Ms. Darsey: Yeah, but you want to make it so high. What's the purpose of making it that high?
> S (girl): I just. I have an idea. I was gonna to do something like that, but then I'm going to –
> Ms. Darsey: But why, but why do you need to make it that high?
> Girl: I - I don't know. I was just had this idea –
> (Whole Class Video)

Here, Ms. Darsey is clearly questioning the decision to make the bridge so high, but still does so in a relatively indirect way. In five episodes within Ms. Jarvis's classroom, Ms. Jarvis provided direct advice to avoid design failures, for example suggesting at the beginning of the Plant Packages unit that students worry more about design performance than cost:

> Ms. Jarvis: And here we go, okay. You - you first must meet the needs of your plant and your consumer, secondly try to reduce the cost. This is the problem we had with the bridges. You were mostly concerned about the cost -
> Student: Instead of the other things.
> Ms. Jarvis: - and instead of the other things -
> Multiple students: [chatter]

> Ms. Jarvis: And we didn't have successful bridges. Since - since you knew - since you know you're going to get to improve, my recommendation Grace, is to - the first go round - not worry too much about cost at all, and then when you get to improve that can be the thing that you try to improve on.
> (Whole Class Video)

At the end of this episode, Ms. Jarvis reminded students that they will have a chance to try again, which she mentioned in two episodes, as did Ms. Darsey. For example, Ms. Darsey shared with her class:

> After design number 1, you might find out - 'Oh, that worked pretty good. I might just want to maybe tweak it.' And some of you might be like, 'aw, man - I've got a lot more thinking to do, so I'm going to really have to rethink this design,' right? So some of you might find that you're tweaking. And some of you might find that you're redesigning. Either one is fine. Okay, 'cuz in the real world some engineers tweak, and some of them have to go back to the drawing board and redesign. (Ms. Darsey, Whole Class Video)

Collectively, in this and the other instances, both Ms. Darsey and Ms. Jarvis emphasized to students – prior to testing designs or even earlier in the EDP – that their designs may not work, and that engineers often try multiple times to get it right.

Conclusions & Discussion

Through the inclusion of the Improve step, the EDP necessarily includes an opportunity for students to try again. This presents students with the opportunity to fail and – through failure analysis and improvement – to learn from failure. This is not only representative of the real work of engineers, who iteratively improve their designs multiple times and for whom design failure is a normative experience (Petroski, 2012), it is also supportive of calls for students to enact a growth mindset, learning from failure experiences and developing resilience (Dweck, 2008).

This study has enhanced previous research on student and teacher responses to design failure as reported by teachers (Lottero-Perdue & Parry, in press for 2015). Importantly, it utilizes video data at its core to locate evidence of how students and teachers respond to design failure during instruction, with supporting evidence from student journals, teacher Post-teaching Interviews, and student Post-unit Interviews. In Ms. Jarvis' and Ms. Darsey's classroom, it is evident that students respond both positively and productively and negatively and non-productively to design failures, with the most obvious of these responses summarized in Table 11. In addition, students anticipated the possibility of both design failure and, more regularly, design success in the early stages of the design process.

Teachers responded to student design failures in these early stages, as well – anticipating student failure and forewarning students that it may occur and if it does, "it's okay," especially because they, like practicing engineers, get to try again. Ms. Darsey and Ms. Jarvis responded to design failures in ways that were consistent with responses reported by teachers in the Lottero-Perdue & Parry (in press for 2015) study, yet analysis of video and other data sources revealed two important additions: 1) reminding students about proper testing procedures and constraints, and 2) offering judgment about the success or failure of student designs, which is particularly important when proper testing procedures and constraints are not followed by students.

Table 11. Student responses to design failure evident from video footage.

Resilient, Productive Actions	Non-Resilient, Non-Productive Actions
Engaging in failure analysis Focusing on improvement Referencing background information	Giving up or losing interest Engaging in negative team dynamics Ignoring background information, especially testing procedures
Positive Emotions / Identities	**Negative Emotions / Identities**
Expressing a positive emotion	Expressing a negative emotion

The first of these teacher responses may not seem like a response to design failure, yet it is an essential pre-emptive response. Following correct testing procedures and properly applying constraints is an important precursor to students accurately identifying design failures and then being able to respond to them via failure analysis and improvement (two of the positive, resilient and productive student responses to design failure). As mentioned in the findings section, across all four units and both teachers, student teams often neglected to follow correct testing procedures, disabling them from valid failure analysis and subsequent improvement. This was true for the first Oil Spill design in Ms. Darsey's class, where the Focus Team did not accurately assess the amount of oil left on the water when they inaccurately performed the Water Oil Detection Test. The test was followed correctly for the second design, once Ms. Darsey intervened to review proper testing procedures. In other cases, when teams incorrectly performed the Shore Oil Detection Test, Ms. Darsey re-performed the test for the teams. In this way, she not only offered a reminder of correct testing procedures, but also provided judgment about the success or failure of this part of the teams' designs.

Given these essential teacher responses, an important addition needs to be made to the simple model of student and teacher responses to design failure presented in Figure 2. This addition, shown in Figure 5, occurs prior to the "Design Failure" box in Figure 2. It is represented as a decision tree, and shows two red, bold-lined boxes each of which represent a lost opportunity for students to learn from design failure. Note that one of these lost opportunities to learn from failure is because testing procedures have been followed, constraints have been properly applied, and the design meets every aspect of the design criteria to the fullest extent; this is an unlikely, but possible outcome. The other lost opportunity to learn from design failure is because testing procedures have not been followed property or constraints not applied, and no intervention was successful to correct one or both of those. Note that the triangular intervention may be made by the teacher or the students, either of whom could enforce proper testing procedures and apply judgment regarding design success/failure. This is labeled as a "successful" intervention to assert that the intervention involves the most accurate enactment of testing procedures and assessment of design success/failure possible.

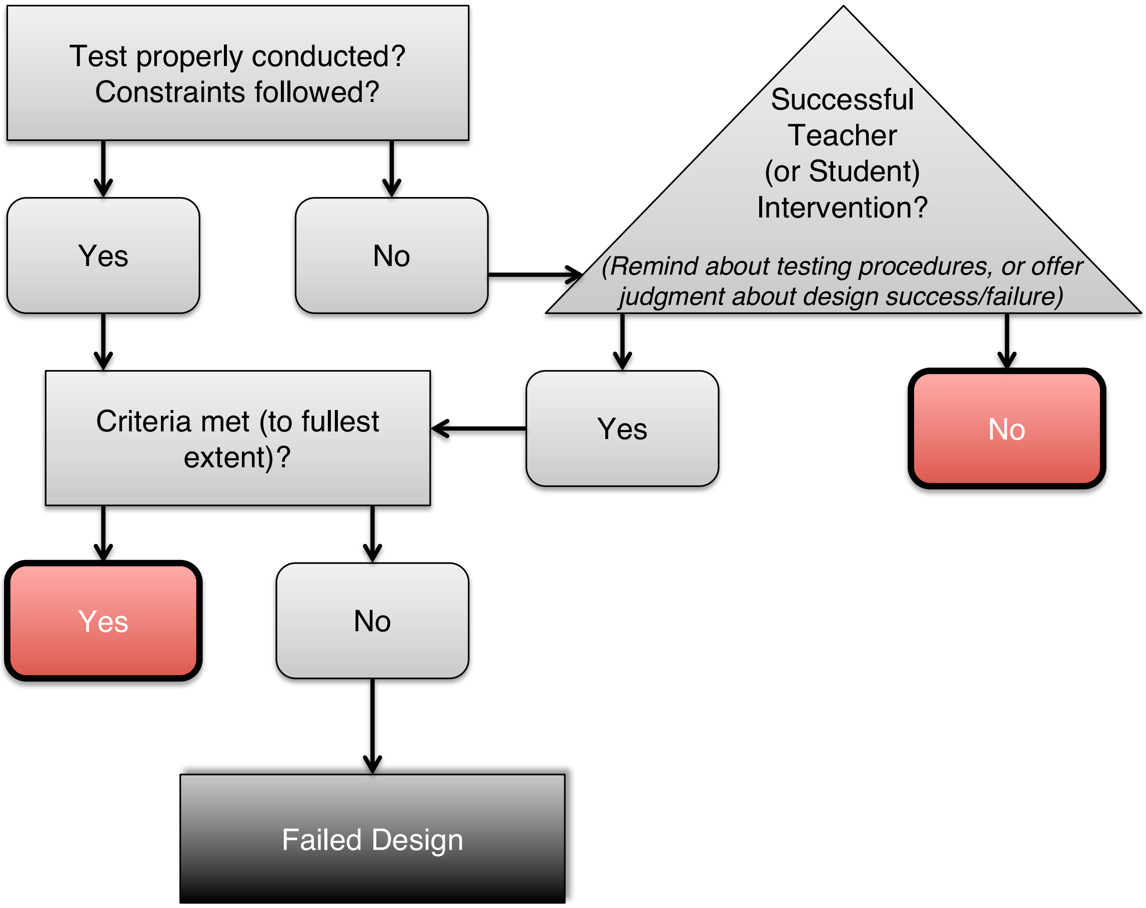

Figure 5. Addition to the student-teacher response to failure model: Valid testing procedures and application of constraints as precursors to learning from failure.

The model presented here is useful because it emphasizes that responding to design failures and learning from failure necessitate that design failure has occurred and can be accurately described, allowing for students (and teachers) to: 1) enter the Figure 2 student-teacher response to failure model, and 2) engage in subsequent failure analysis and improvement. If design failure is not accurately characterized, then how students and teachers respond to the design and engage in failure analysis is convoluted and confusing, and a reason-based improvement process is compromised.

There are multiple reasons why students may not follow testing procedures or apply constraints properly. It is important to recall that Ms. Darsey and Ms. Jarvis were teaching the EiE units for the first time during this study. In some cases, they were unclear about testing procedures and constraints (e.g., in the bridge unit with respect to where the cup of hex nuts was supposed to be placed, which was not clear in the curriculum). They both looked forward to their second year of involvement on the project since they had learned so much about implementation, including and beyond the importance of clearly articulating and reinforcing testing procedures and constraints. In addition, it's important to consider that teams are expected to self-evaluate, and often evaluated their bridges, oil spill processes, and plant packages at different times during class sessions. With roughly eight teams working at different paces in the classrooms busily and often noisily creating and conducting tests, it can be difficult for teachers to monitor each team's testing process.

Future work on the FEED Project will involve analysis of two additional classrooms during the same year of implementation, both of which learned the EiE Unit, *A Stick in the Mud: Evaluating a Landscape* (EiE, 2011d). These classrooms include a more diverse population of students than served by Ms. Jarvis or Ms. Darsey. Video and other data from these units will be analyzed to consider how they resonate with and expand the ideas shared in the present study. Further, cases will be generated from all four FEED Project teachers to describe for each of the four classrooms: how students and teachers respond to design failures, how fail words are used, and what perspectives about failure are held by Focus Team members and the teacher.

Additionally, two of the four classrooms were followed for a second year of data collection. Student and teacher responses to failure will be examined for these classrooms, and compared to first year data. One hypothesis – and that word is used here in a very broad sense – with regard to this work is that perhaps more students in the second year will have opportunities to learn from design failure as teachers are more accustomed to the curriculum and to clearly articulating the testing procedures and constraints.

There is much work to be done with regard to the topic of design failure as it occurs within science-situated engineering education. Other questions to be explored in this area include: How do diverse students respond to design failures? How do teachers of diverse students position failure, use fail words, and engage students in failure experiences? and How do different curricula provide opportunities for students to learn from design failure?

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[i] See Lottero-Perdue & Parry (2014, 2015) for a more thorough description of the E4 Project.

[ii] The two other school sites for the FEED Case Study Project are more socioeconomically, ethnically, and racially diverse.

[iii] Teacher names used in this paper are pseudonyms.

[iv] Ms. Jarvis taught two classrooms of students, one of which is featured within the present study and the FEED Case Study Project; the other classroom, which had 30 students, was not observed.

[v] Student names used in this paper are pseudonyms.

[vi] The tests have slightly different names in the curriculum; these names are being used here for clarity.

[vii] It is important to note that this was Ms. Jarvis's and Ms. Darsey's first time teaching each of these units.