Student Strategies for Collaborative Disciplinary Decision Making in an Elementary Engineering Teaching Experiment

A thesis submitted by

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Abstract

Elementary engineering education is implemented in a wide variety of ways, from after-school programs to student-led outreach to fully integrated, standards-based classroom instruction. In all of these, students are expected to perform complex practices of engineering while (usually) working in collaborative teams, which presents a slew of challenges to novice learners. To explore the sources of and potential tools for navigating these challenges, we designed a teaching experiment to support students in decision-making and groupwork. In this thesis I 1) describe the theory and instructional reasoning that informed the design of the teaching experiment and 2) present a comparative case study analysis of two groups in the fourth-grade classroom. I found three student strategies that facilitated collaborative disciplinary decision making during the engineering design challenge: talking about plans, responsive discussion, and naming. These strategies further characterize the ways elementary students engage in engineering and reinforce the importance of argumentation as a skill and a practice for young engineering learners.

Acknowledgements

Thanks to Kristen Wendell without whom I would not even be at Tufts, let alone have written this thesis. Your patience, kindness, and brilliance cannot be overstated. Without our weekly meetings full of your encouragement and my scrambling to remember the words you said in the order you said them, this would not exist! Thanks to my friends and family for reminding me every five seconds that I should be working, but also that I could do it, and making sure I had all the candy, sleep, and time in a tiny house to make this happen. A huge thank you to Karen Miel, without whom this teaching experiment would not exist! Thank you for your curiosity about kids crying in engineering, your vigilant attention to issues of equity, and your patience as we juggled designing, teaching, and recording all of this. Thank you to Ryan for playing along with our curriculum ideas and being an awesome, observant, and thoughtful STOMPer. Thank you to David Hammer and Chris Rogers for the wisdom and diverse perspectives you brought to my committee.

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Introduction

Elementary engineering education is implemented in a wide variety of ways, from after-school programs to student-led outreach to fully integrated, standards-based classroom instruction. In all of these, students are expected to perform complex practices of engineering while (usually) working in collaborative teams. Both a colleague, Karen Miel, and I have been interested in the balance and, often, the tensions between these two things. In our experience in various projects, we observed the make-or-break effect of collaboration on productive engineering in elementary school. The highest tensions often arose at points of decision making; students trying to decide between multiple ideas, all generated by different groupmates, got tangled in the web of interpersonal relations, often leaving science and engineering reasoning behind. In the worst cases, this led to screaming matches; in the best cases, begrudging compromises, popularity contests, or manipulative votes.

To explore the sources of and potential tools for navigating these challenges, we designed a teaching experiment featuring a series of engineering challenges and tools for scaffolding decision making and groupwork. The teaching experiment was implemented from October to December 2018 as part of the Student Teacher Outreach and Mentorship Program (STOMP) and served as the curricular context for this thesis. Over the course of the semester we collected data including student work, video and audio of class sessions, and clinical interviews. In this thesis, I describe the design of the curricular supports of the teaching experiment and analyze some of the groupwork dynamics related to collaborative decision making. The findings of this thesis are organized in two parts which address the following objectives:

1. Describe the theory and instructional reasoning that informed the design of the teaching experiment, including the scaffolds for decision making and groupwork.

2. Analyze the strategies employed by a productive group that facilitated collaborative decision-making during the engineering design challenge, including how these were influenced by the designed elements of the teaching experiment.

To address the first objective, I use conjecture mapping, a technique from design-based research that charts how the elements of a learning environment are theorized to produce certain outcomes. I employed a grounded theory approach with two contrasting cases to examine productive collaboration strategies in the classroom.

Theoretical Framework

I approach this work from the perspective of sociocultural learning and situated learning theory, where learning takes place in communities of practice (Lave & Wenger, 1991). Elementary students, novices to engineering, were introduced to some of the practices of engineering through this teaching experiment. Engineering practices, like collaboration or argumentation, rely heavily on language. In accordance with linguistic anthropological traditions, Elinor Ochs theorized that language socialization is helplessly intertwined with sociocultural socialization, like that described by Lave and Wenger, and occurs through authentic use and practice of the language being acquired. As novice engineers begin to practice the language of the discipline, they can be said to acquire the language and culture of expert engineers. Ochs defines culture as "a set of socially recognized and organized practices and theories for acting, feeling, and knowing, along with their material and institutional products, associated with membership in a social group" (Ochs 1996). As a community, engineers develop special vocabularies and distinct ways of thinking, doing, interacting, and using symbols and tools (Kittleson & Southerland, 2004). In light of this definition of culture, when students engage in the practices of acting, feeling, and knowing like an engineer, they acquire the language of engineering and are socialized as engineers.

This perspective emphasizes the importance of providing students with opportunities to engage with disciplinary tools and discourses in ways that are authentic to engineering communities. In this teaching experiment, we developed tools to support students' discursive practices, both through "engineering groupwork norms" and by having them use data sheets and a decision matrix, tools particularly useful in engineering design projects. The engineering groupwork norms were intended to serve as scaffolds for discursive practice, supporting both students' engagement in the culture and language practices of engineering. Using the decision matrix, an authentic engineering tool that has developed in professional practice, allowed students to engage in practices and ways of thinking and doing that are unique to engineering. Because I view the relevant learning from this teaching experiment as being socialized into the practices of engineering, it was important to examine student-to-student interactions for evidence of engagement with engineering.

Background

At the core of this thesis lies the teaching experiment, which incorporates ill-structured design challenges to provide students with an engineering experience. Though the engineering design challenge is widely used as a structure for doing engineering in educational settings (NAE and NRC, 2009), there are still questions about how to organize them to promote different learning outcomes within the discipline, including issues about the competitive nature of engineering design, how to promote productive collaboration, and how to support students in decision making and argumentation. This study builds upon previous work exploring these areas, informed by scholars who have worked to address these questions.

In highlighting the often-competitive nature of engineering design challenges, Sadler, Coyle and Schwartz (2000) describe principles that reduce competition and promote collaboration through the use of "tests against nature, large dynamic ranges in performance, initial prototype designs, and alternative methods of recording and presenting results." They also argue that design challenges presented to young students should have goals that are easy to understand and create a need for systematic testing of design variables (Sadler, Coyle, & Schwartz, 2000).

Engineering design challenges are usually done in collaborative teams, which come with their own slew of difficulties for students. In her work studying campus culture and undergraduate engineering students, Tonso highlighted the importance of respectful social interactions in effective teamwork, leading to high quality engineering products (Tonso, 2006). She recommends paying attention to the "full range of student teamwork behaviors, and to both technical and non-technical teamwork, and to their underlying connections back to campus cultures" (Tonso, 2006). In her study, technical work was related to the science and engineering principles governing the engineering project the undergraduate students were completing; non-technical work pertained to the process tasks, like managing files, that were critical but undervalued tasks. Though this study of undergraduate students involved analyzing the campus culture, parallels can be drawn to the classroom cultures that exist in elementary school.

In their work with fifth grade students doing robotics design challenges, Jordan and McDaniel (2014) examined the influence of peer interaction while students managed the uncertainties inherent to solving an ill-structured problem collaboratively. They identified patterns of peer response, both supportive and unsupportive, and found that students relied on supportive peer responses to enact uncertainty management strategies (Jordan & McDaniel, 2014). In his early studies of engineering activities in elementary school settings, Roth examined the flexible nature of decision-making. He found that peer relations and garnering sufficient social support influenced decision-making more than pure scientific or engineering reasoning; often "a final decision emerged not as the result of a deductive conclusion from all the available options, but as that course of action with the least constraints or negative tags" (Roth, 1995).

These findings position managing peer relations as an integral part of collaborating in engineering, sometimes dominating the decisions and progress that student groups can make. While managing peer relations, students articulate and defend their design ideas to each other and balance the criteria and constraints of the design problem. These activities are captured in the *reflective decision making* (RDM) framework proposed by Wendell, Wright, and Paugh (Wendell, Wright, & Paugh, 2017) from a study of elementary students planning and redesigning during an engineering design challenge. RDM has six elements: articulating multiple solutions, evaluating pros and cons, intentionally selecting a solution, retelling the performance of a solution, analyzing a solution according to evidence, and purposefully choosing improvements. I posit that engaging in these behaviors to make reflective decisions, and thus reach a deductive conclusion, requires students to engage in argumentation.

Argumentation in science education has been well-characterized (Kuhn, 2010; McNeill & Pimentel, 2010; J. Osborne, Erduran, & Simon, 2004; J. F. Osborne & Patterson, 2011); many tools and strategies exist for supporting argumentation in science. For instance, from a study of unexpectedly passionate argumentation among fifth-grade students in science class, Engle and Conant (2002) propose four principles of the learning environment that fostered *productive disciplinary engagement:* problematization, student authority, accountability to shared norms, and the provision of relevant resources. Less is known about how to specifically foster this level of engagement in argumentation in engineering. In a recent review of the argumentation literature in K12 engineering, Wilson-Lopez et al. (2018) note a *lack* of test-based evidence in argumentation in novice engineering. They suggest having students "argue for or against their own designs more frequently, using tests of design prototypes to support their claims" and for classrooms to incorporate "controlled tests of design prototypes."

Because elementary students are novices to these practices of engineering (managing peer relations and uncertainty, evidence-based decision-making, and argumentation) they require support as they acquire them. McFadden and Roehrig (2018) observed students struggle to adopt the practices and discourses of engineering with only verbal supports as they used design drawings to explain their ideas. They recommend using written supports to help students "overcome the uncertainty that arises during an EDC [engineering design challenge] without placing boundaries on their imagination" (McFadden & Roehrig, 2018). In general, there is a call for tools and strategies specific to engineering to bolster student decision making and argumentation based on experimental evidence (McFadden & Roehrig, 2018; Wendell et al., 2017; Wilson-Lopez et al., 2018). The teaching experiment described in this thesis was designed to incorporate recommendations about implementing design challenges in elementary school and explore potential tools and strategies to achieve the outcomes of more evidence-based decision-making and reduced negative effects of social tensions in engineering. I used the conjecture mapping technique, outlined in *Part I: Design of the teaching experiment*, to retrospectively unpack how we expected the tools and strategies we designed to produce these desired outcomes.

Participants and Curricular Context

This study took place within the STOMP engineering outreach program run by Tufts University. This program matches pairs of university students with local elementary schools to facilitate engineering in their classrooms for one hour per week. Typically, the university students develop and teach the curriculum; for this teaching experiment, the curriculum was designed by me and a colleague (a doctoral student in STEM education) to scaffold collaborative groupwork and decision making. This is explained in greater depth in *Part I: Design of the teaching experiment*. I cotaught this implementation with an undergraduate student (Ryan, a sophomore majoring in Data Science) in a socioeconomically, racially, and linguistically diverse fourth grade classroom in a suburban school district. Of the 20 participating students, 11 were female, 9 were male, 11 were White, and 9 were People of Color.

The semester consisted of eight, 1-hour sessions split into three foci: an engineering warm up, a rocket design challenge, and a flamingo leg brace design challenge. Table 1 outlines how the eight sessions were distributed within these foci and the main activities of each session.

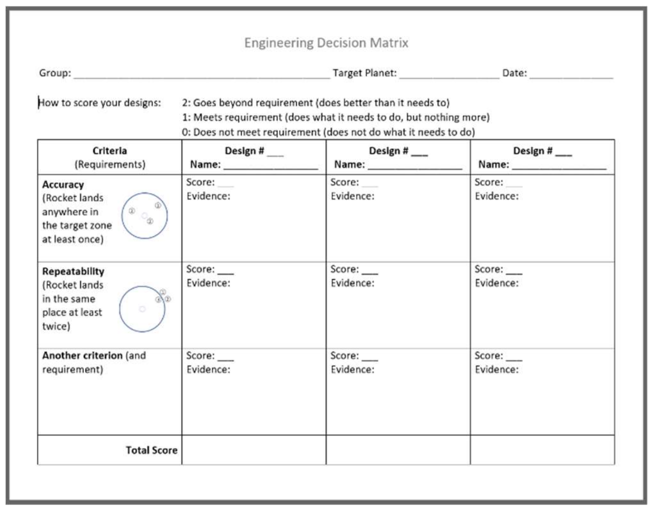
Table 1. Classroom semester overview. This thesis focuses on the days highlighted in gray.

Focus	Session #	Main session activities
Engineering warm up	1	Discussion of engineering group norms, brainstorming activity
Rocket design challenge	2	Intro to challenge, build and test rocket prototypes
	3	Build and test rocket prototypes
	4	Decision matrix, peer feedback, refine designs
	5	Final build, whole class share out, debrief challenge
Flamingo leg brace design challenge	6	Intro to challenge, build and test
	7	Build and test leg braces, decision matrix
	8	Design expo, semester wrap up

This thesis focuses on the rocket design challenge: create a rocket that can travel to a designated planet, represented by a hula hoop. Students worked in teams of three to build their rockets from an abundance of craft materials. They launched their rockets using a stomp rocket launcher-- a plastic tube mounted on a tripod and powered by a burst of air from stepping (or often, jumping) on the bladder, as shown in Figure 1.

Figure 1. Students using the stomp rocket launcher.

On the first day of the rocket design challenge (Rockets Day 1), we introduced students to the challenge, positioning them as engineers working for NASA, trying to get a craft on every planet in our solar system. We demonstrated how they would launch their rockets and record the results on a data sheet, assigned target planets, and gave them the remainder of the session to build and test their prototypes. We introduced them to a central tool of the teaching experiment: the decision matrix (Figure 2). Decision matrices are common in professional practice to assist engineers in weighing criteria and constraints to systemically optimize their solutions (Kelley, 2010; Ullman, 2010). They often appear as tables of design options against criteria or requirements where weighted scores are assigned. I describe the design of the particular decision matrix scaffold from this teaching experiment in detail in



Engineering Decision Matrix

Group: ______ Target Planet: ______ Date: ______

How to score your designs: 2: Goes beyond requirement (does better than it needs to)
1: Meets requirement (does what it needs to do, but nothing more)
0: Does not meet requirement (does not do what it needs to do)

Criteria (Requirements)	Design # ___ Name: ______	Design # ___ Name: ______	Design # ___ Name: ______
Accuracy (Rocket lands anywhere in the target zone at least once)	Score: ___ Evidence:	Score: ___ Evidence:	Score: ___ Evidence:
Repeatability (Rocket lands in the same place at least twice)	Score: ___ Evidence:	Score: ___ Evidence:	Score: ___ Evidence:
Another criterion (and requirement)	Score: ___ Evidence:	Score: ___ Evidence:	Score: ___ Evidence:
Total Score			

Figure 2. Decision matrix worksheet completed by students in the classroom.

Part I: Design of the teaching experiment. After showing this to the students, we told them that later they would be using it to decide between their different ideas and we encouraged them to build as many ideas as they could.

On Rockets Day 2, we began by demonstrating how to fill out the decision matrix. We showed them a data sheet for a rocket that we had built and tested and had the class evaluate it together. After this demo, they spent the remaining 45 minutes continuing to build and test rockets. We had intended for them to complete the decision matrix at the end of this session, but students were so engaged with the building process we wanted to give them time to develop all the ideas they were having. We took a break from the building and testing process on Rockets Day 3 to have student groups fill out a decision matrix, plan their next design, and share these plans in a peer-to-peer feedback session. After the feedback, students had a few minutes to make any changes to their designs. On Rockets Day 4, the final day of the design challenge, students built the rockets they had planned the week before. Students tested their final prototypes in front of the class before debriefing the design challenge in a whole-class discussion. Examples of student rocket prototypes can be seen in Figure 3.

Figure 3. Student rocket prototypes, built from craft materials like foam, paper cups, and tape.

This unit flow was inspired by the Engineering is Elementary (EiE) “Liftoff: Engineering Rockets and Rovers” curriculum (Engineering is Elementary, 2014), one that has been drawn on for previous implementations conducted by colleagues (Wendell, Andrews, & Paugh, 2019). This particular enactment included scaffolds for decision making and collaboration, the development of which is described in Part I.

Part I: Design of the teaching experiment

One method for charting how theory informs the design of a learning environment that is prevalent in design-based research is *conjecture mapping*. Conjecture mapping entails linking embodiments, mediating processes, and outcomes of a teaching experiment through design conjectures and theoretical conjectures under the umbrella of a high-level conjecture that is guiding the design (Sandoval, 2014). I choose to use this method because it summarizes and explicates the hypothesized learning trajectory (Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003) of the designed learning environment (Sandoval, 2014). Sandoval proposed conjecture mapping as a response to critiques of design based research lacking an “argumentative grammar” or “the logic that guides the use of a method and that supports reasoning about its data” (Kelly, 2004). The elements of a conjecture map serve to outline this logic and point to research questions that are directly linked to the design of the learning environment in context. In this thesis, I used conjecture mapping retrospectively to reflect on the design of the teaching experiment, the literature that informed our decisions, and the learning trajectory that we hypothesized for the students. In a conventional design-based research study, research questions would emerge from evaluating the truth-value of design and theoretical conjectures embedded in the conjecture map. Because I used the conjecture map as more of a tool for organization and reflection, the question guiding *Part II: Comparative case study analysis* stems from the overall goal of the teaching experiment in supporting collaborative, disciplinary decision-making, rather than growing directly from the conjecture mapping technique.

The design of this teaching experiment was influenced by two main objectives:

1. Apply recommendations from previous engineering education studies to structure a research-informed engineering design challenge in a 4th grade classroom.
2. Facilitate collaborative, disciplinary decision making during a design challenge that …
    a. incorporates engineering discourses and
    b. is rooted in science and engineering reasoning.

The first objective, structuring a research-informed design challenge, draws from sources concerning both recommendations for effective design challenges (Sadler et al., 2000) and groupwork strategies (Cohen & Lotan, 2014). We incorporated Sadler et al.'s recommendations for developing an effective design challenge into our curriculum by giving each student group a different planet to shoot for (competing against themselves), showing the class a sub-par prototype that the instructors made, requiring at least three different rocket designs (iteration), having students keep track of iterations and test results on data sheets (purposeful record keeping), and incorporating a decision making scaffold. These recommendations stem from the authors' extensive, iterative work designing engineering challenges with teachers in 12 schools in the United States with 5th-9th grade students. Cohen and Lotan, both professors at Stanford and experts in sociology and education, wrote *Designing Groupwork* to share their ideas about cooperative learning, built from years of research and teaching experience, with an audience of educators. Strategies from the Cohen and Lotan book informed our design and inclusion of a set of "engineering groupwork norms." During the teaching experiment, we discussed these norms on the first day of class and displayed them on chart paper at the front of the classroom each following week.

The focus on groupwork norms also supported the second objective, fostering students' engineering discourses. This is grounded in work that has characterized the nature of special discourse practices in engineering (e.g., Kittleson & Southerland, 2004) and ways to support students in developing these discourses (McFadden & Roehrig, 2018). Kittelson and Southerland reinforce what is known from discourse analysis, that various communities develop their own discourses (Ochs, 1996), and apply the idea specifically to engineering; "in addition to using multiple modes of expression, specific communities of engineering designers develop special vocabularies of technical language as well as distinct ways of thinking, doing, interacting, and using symbols and tools together" (Kittleson & Southerland, 2004). Conclusions from McFadden and Roehrig (2018) support the choices to include groupwork norms, data sheets, and a decision matrix to both support students in developing engineering discourses and managing uncertainty when working in groups.

Other important engineering discourses are embedded within the reflective decision-making framework (Wendell et al., 2017). The teaching experiment centered around the use of a decision matrix to compare multiple solutions and use data from test trials to make an informed decision for the next iteration, supporting the elements of reflective decision-making: articulating multiple solutions, evaluating pros and cons, intentionally selecting a solution, retelling the performance of a solution, analyzing a solution according to evidence, and purposefully choosing improvements. In their review of engineering education literature, Wilson-Lopez et al. recommend having students argue for their designs using evidence from controlled tests of prototypes (2018). They found this to be lacking in elementary engineering classrooms, yet this practice is integral in the reflective decision-making framework to perform actions like "analyzing a solution according to evidence" and "evaluating pros and cons." These practices are closely related to optimization, or weighing criteria and constraints to systematically locate the optimum design solution (Kelley, 2010; Kelley, Capobianco, & Kaluf, 2015). We scaffolded optimization through a decision matrix, a recommended pedagogical support (Kelley, 2010) and common professional tool (Ullman, 2010). We designed the decision matrix, described in more depth below, to help students engage in the practices of reflective decision making and evidence-based argumentation.

Conjecture mapping

Figure 4 shows the conjecture map developed for this teaching experiment. The first component of the conjecture map is a *high-level conjecture*, which acts almost as the philosophy of the learning environment; it drives the design by summarizing the flow from designed embodiments to observable mediating processes to expected outcomes. This teaching experiment was guided by the following high-level conjecture:

> *The use of groupwork norms and a decision matrix during an elementary engineering design challenge will support evidence-based decision making and serve to reduce unproductive social tension and increase productive content friction.*

This conjecture captures the second objective we had in designing this teaching experiment (facilitate collaborative, disciplinary decision making during a design challenge that incorporates engineering discourses and is rooted in science and engineering reasoning) and connects it to the actual tools we implemented and outcomes we desired. The arrows in Figure 4 connect the elements of the conjecture map and represent other types of conjectures: embodiments are related to some or all mediating processes through *design conjectures*, which are projected to produce some or all outcomes through *theoretical conjectures*. In this way, the conjecture map is a means of explicating our hypotheses about how the components of the learning environment are related (Sandoval, 2014).

Design conjectures: connecting embodiments and mediating processes

Embodiments refer to the things that one can design; in a way, they are the independent variables in a design-based research study. They reify the ideas embedded in the high-level conjecture in the classroom. In this teaching experiment, embodiments include the tools of the engineering decision matrix and data sheet, the discursive practices proposed through "engineering groupwork norms," and the task/participant structures of designated discussion time, working in teams, and working towards one deliverable per team. *Design conjectures* describe how a given embodiment is expected to foster one or more *mediating processes.* Mediating processes are the behaviors and activities we can observe in the data we collect. For instance, the completed decision matrices collected from the students serve as participant artifacts that could show the students using data and reasoning to inform their designs and designing their next iteration based on the decision matrix. Through classroom video data, we may observe desired interactions and aspects of the embodiments that cued them. In this teaching experiment, these interactions include the discussion of ideas in relation to the decision matrix, explicit linguistic references to the groupwork norms, and all team members contributing to the project. In the following subsections, I outline each of the embodiments, their evolution throughout the design of the teaching experiment, the literature that informed their design, and the mediating processes they were expected to generate.

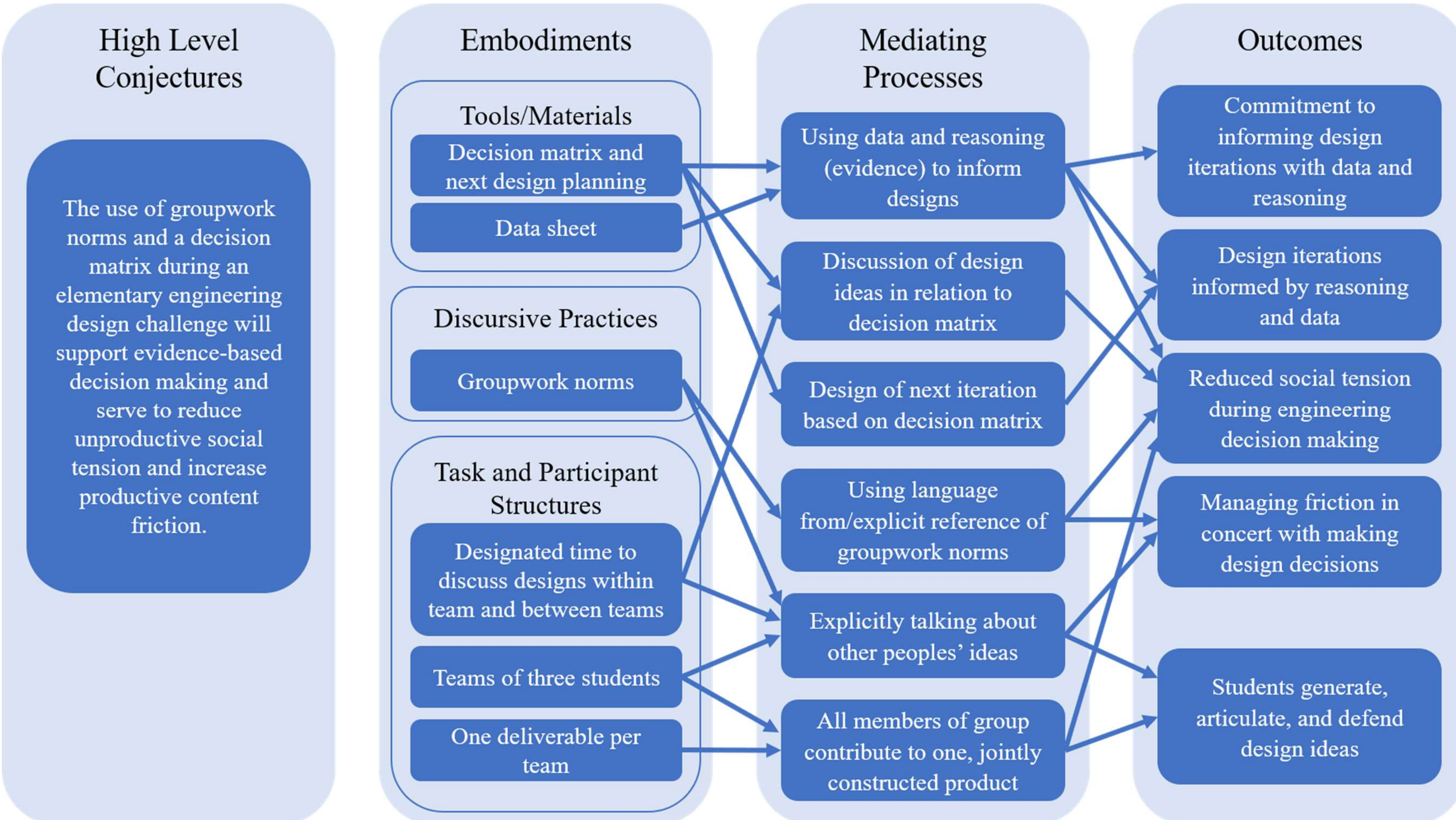
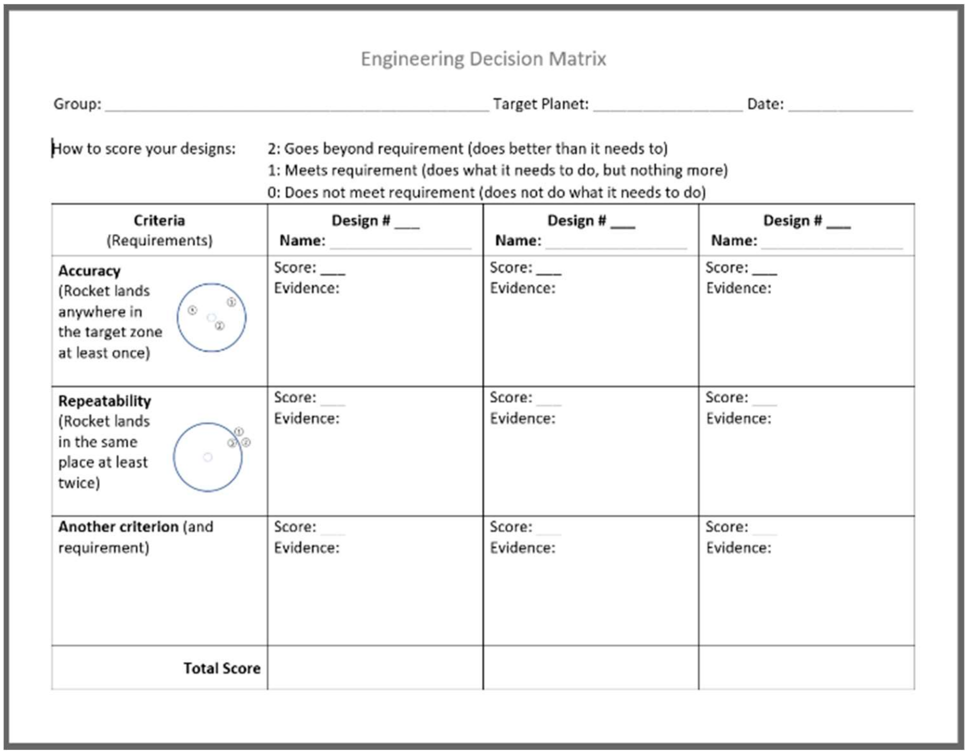


Figure 4. *Conjecture map for the teaching experiment.*

Decision matrix and next design planning worksheet

The decision matrix is a tool common in professional practice to assist engineers in weighing criteria and constraints to systemically optimize their solutions (Kelley, 2010; Ullman, 2010). During this teaching experiment, we had students complete the decision matrix midway through the design challenge to encourage evaluating previous prototypes in service of designing a future prototype. These distinct but related activities were scaffolded through two worksheets, to be completed as a design team. Because this was the student's first exposure to this tool, this activity was heavily directed by the instructors. We intended for the students to have more agency over how and whether they used a decision matrix in the second design challenge of the semester.

We designed the first worksheet, the decision matrix (Figure 5), to help students compare three of their prototypes against two prescribed criteria, accuracy and repeatability, and a criterion of their own devising. Students assigned a score to each design for each criterion, along with evidence for their evaluation. Criteria were not weighted and the definition of scores was predetermined ("How to score your designs," Figure 5). The second worksheet presented questions for students to consider when planning their next design iteration and space to sketch their design (Figure 6). The questions in the "Discuss" section were intended to encourage groups to talk together about their next steps and how to incorporate their evaluations from the decision matrix into their next iteration; the "Plan" section encouraged practical considerations like materials, attachments, and shapes, as well as reasoning for each of these design decisions.



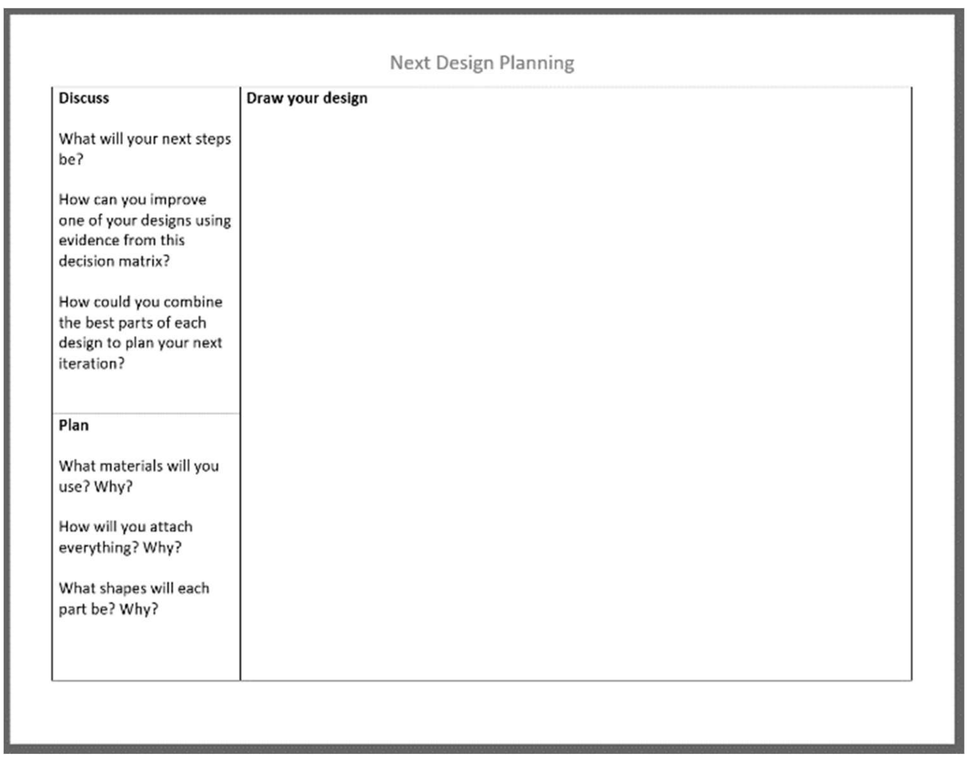
Engineering Decision Matrix

Group: _________________________ Target Planet: _____________ Date: ____________

How to score your designs: 2: Goes beyond requirement (does better than it needs to)
1: Meets requirement (does what it needs to do, but nothing more)
0: Does not meet requirement (does not do what it needs to do)

Criteria (Requirements)	**Design # ___** **Name:** ________	**Design # ___** **Name:** ________	**Design # ___** **Name:** ________
Accuracy (Rocket lands anywhere in the target zone at least once)	Score: ___ Evidence:	Score: ___ Evidence:	Score: ___ Evidence:
Repeatability (Rocket lands in the same place at least twice)	Score: ___ Evidence:	Score: ___ Evidence:	Score: ___ Evidence:
Another criterion (and requirement)	Score: ___ Evidence:	Score: ___ Evidence:	Score: ___ Evidence:
Total Score			

Figure 5. Front side of the worksheet, decision matrix.



Next Design Planning

Discuss What will your next steps be? How can you improve one of your designs using evidence from this decision matrix? How could you combine the best parts of each design to plan your next iteration?	**Draw your design**
Plan What materials will you use? Why? How will you attach everything? Why? What shapes will each part be? Why?	

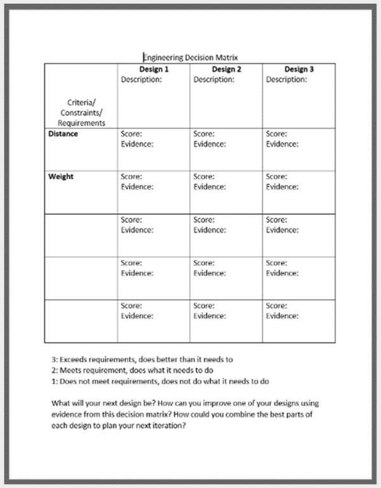
Figure 6. Back side of the worksheet, next design planning.

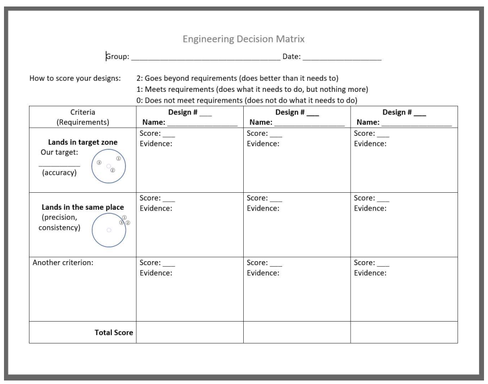
The final form of the worksheets described above was the result of five rounds of iteration. The table below (Table 2) depicts the evolution of the decision matrix worksheet through the three most significantly different versions. The table includes a picture of each version, key features, changes from the previous version, and reasons for those changes. The decision matrix worksheet was tested with adult colleagues and the language was refined with help from their elementary aged children. I've included this table to document the thinking and iteration that went into the design of the decision matrix; tracking the changes we make to elements of the learning environment is a central tenet of design-based research methodology (Collins, Joseph, & Bielaczyc, 2004).

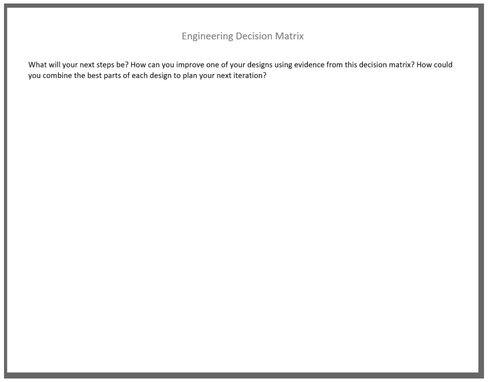
We anticipated three mediating processes to occur while students evaluated their prototypes with the decision matrix and planned their next design: "discussion of design ideas in relation to decision matrix," "using data and reasoning (evidence) to inform designs," and "design of final solution based on decision matrix." These design conjectures were built into the decision matrix; for instance, on the "Next Design Planning" side of the worksheet, the section labeled "Discuss" prompts students to consider how the completion of the decision matrix will inform their next design. Having the score box also include a prompt for evidence invites students to consider their test results and bring reasoning into their evaluations. The "Plan" questions on the "Next Design Planning" side of the worksheet followed with "Why?" are intended to push students to defend the choices they make for their next design, ideally with the evidence they gathered and discussed while completing the decision matrix.

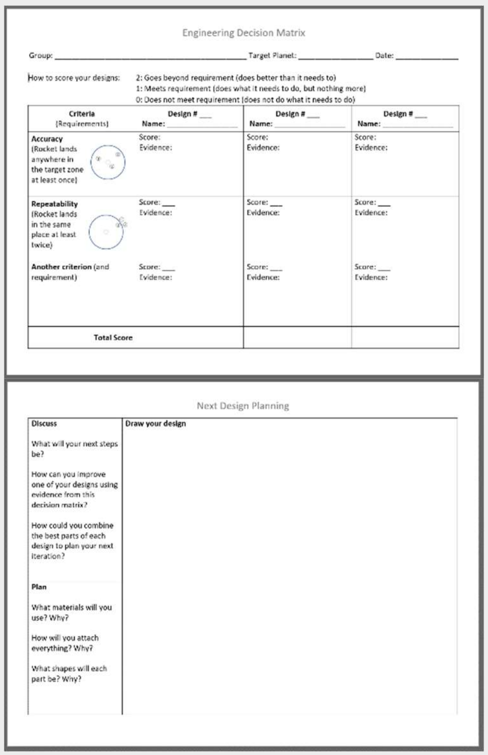
Table 2. Evolution of the decision matrix, showing three versions, key features, changes from previous version, and reasons for changes.

Version of Decision Matrix	Key Features	Major Changes	Reasons for Changes

	• Compare Designs 1, 2, 3
	• Five criteria/ constraints/ requirements
	  ○ Two prescribed
	  ○ Three student-choice
	• Scores 1-3
	• Questions to think about for planning next design
		N/A	N/A

	• Compare three designs, students provide names and numbers
	• Three criteria with requirements
	  ○ Two prescribed
	  ○ One student-choice
	• Scores 0-2
	• Space to total score
	• Questions to think about for planning next design
	• Blank space to sketch next design
		1. Landscape orientation
		2. Students provide names and numbers for designs
		3. Reduction in number of criteria
		4. Changed criteria to "lands in target zone" and "lands in the same place" to better capture the goals of the design challenge than "weight" and "distance"
		5. Specificity in criteria and requirements
			1. Provides more space for students to write evidence
			2. More flexible for students who build more than three prototypes to evaluate those of their choosing
			3. From testing V1 with colleagues, five criteria were too much to handle in a one-hour period; inventing three criteria was difficult
			4. Because the goal of the design challenge was to land in a target zone, it made more sense to evaluate prototypes based on where they landed rather than the weight of the rocket or pure distance that they traveled
			5. In testing, different groups had different interpretations of the criteria on V1; specifying what each criterion meant

		6. Graphic to illustrate criteria 7. Scores 0-2, not 1-3 8. Space to total score 9. Second page for next design planning with blank space to sketch design 10. “Exceeds requirements” replaced with “goes beyond requirements”	with a requirement intended to solve this issue 6. Graphic illustrated requirement in an accessible way 7. Less likely to tie if prototypes that did not meet a requirement receive a “0” 8. Total scores are simpler to evaluate 9. Blank space invites students to represent their ideas for their next design through sketching 10. Confusion with the term “exceeds” for criteria that are “lower” for a higher score (i.e. a rocket could get a 2 for being the lightest)

	• Compare three designs, students provide names and numbers
	• Three criteria with requirements
	  ○ Two prescribed
	  ○ One student-choice
	• Scores 0-2
	• Space to total score
	• “Discuss” questions for planning next design based on decision matrix
	• “Plan” questions to prompt practical considerations
	• Blank space to “Draw your design”
		1. Space to write “Target Planet”
		2. Criteria renamed “accuracy” and “repeatability”
		3. More specific definition of the requirements (in parentheses)
		4. Second sheet titled “Next Design Planning”
		5. Separate “Discuss” and “Plan” questions
		6. Labeled blank area “Draw your design:”
			1. Because each group had a different target planet, it was necessary to have them record this information
			2. Tested the words “precision” “consistency” and “repeatability” with elementary aged students and “repeatability” cued an interpretation that matched our own; “accuracy” concisely mapped “lands in target zone”
			3. Unambiguous evaluation improved consistency across groups
			4. Separated the two activities more clearly
			5. Wanted to provide students broad questions to think about as a group and specific questions to answer with their sketch
			6. Though a blank space invites sketching, a labeled space directly asks students to sketch their next designs

Data sheets

While testing the first version of the decision matrix with the lab group, the need for a physical record of test results became apparent. This data sheet was conceived as a means of qualitatively recording both what each design iteration looked like as well as how it performed. The first version of this worksheet had space for students to record their group name, the date, design number, design name, a description of the design, a sketch of the design, and a qualitative representation of test results (Figure 7). The blue circle represents the hula hoop that was used to designate the target zone for each group's planet. The major difference between the first version (Figure 7) and the final version that went to students (Figure 8) is the rearrangement of the elements to allow more room for students to sketch their designs and lengthen the test result space to more closely resemble the actual testing area. During the teaching experiment, students were instructed to get a new data sheet every time they changed their rocket design and to record several test results. The data sheets were hypothesized to help students in the mediating process of "using data and reasoning (evidence) to support design decisions" by providing them with a concrete and shared record of their tests.

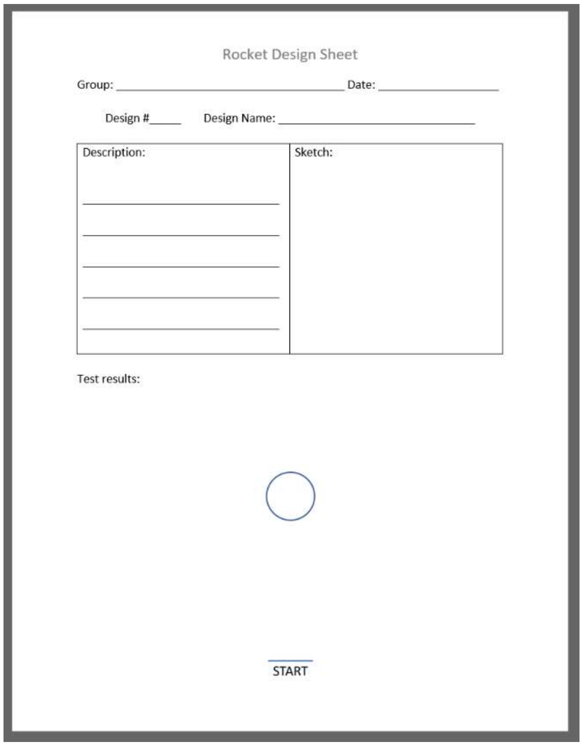


Figure 7. Data sheet version 1.

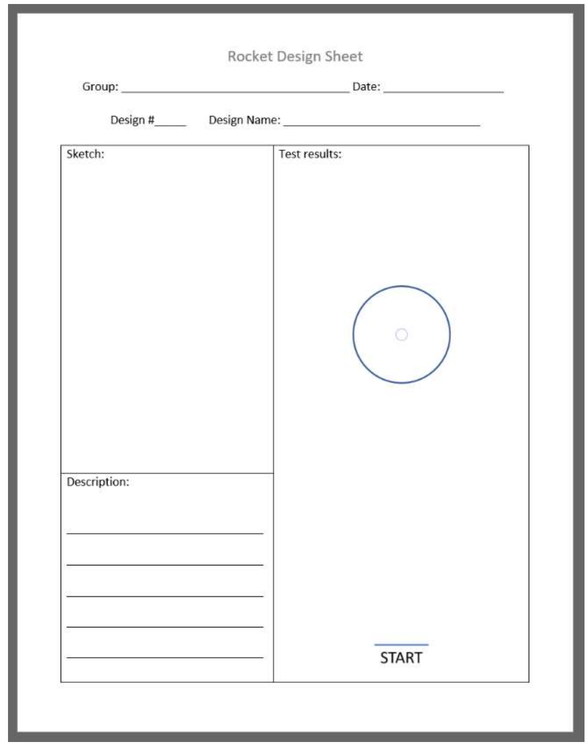


Figure 8. Data sheet version 2 (final).

Engineering groupwork norms

Engineering Groupwork Norms

1) Say your own ideas
2) Listen to others; give everyone a chance to talk
3) Ask others for their ideas
4) Give reasons for your ideas
5) Discuss many different ideas

Figure 9. Engineering groupwork norms.

Collaborative engineering talk was emphasized in this teaching experiment through the Engineering Groupwork Norms (Figure 9). These were derived from *Designing Groupwork* (Cohen & Lotan, 2014), a book aimed at teachers to help them in organizing their classrooms and designing collaborative tasks so that all students participate actively. The book presents four "norms for cooperative problem solving" from a study on teamwork (Morris, 1977). We turned these four norms into the five in Figure 9 by parsing "give reasons for your ideas and discuss many different ideas" into two separate norms. We began the first day of class with a whole class discussion about the engineering group norms. We presented the norms and, for each one, asked students to generate examples of what the norms might look like and nonexamples of possible group interactions that would not be following the norms. After this discussion, we put students were into their assigned groups of three (the same groups they would be in for the rocket design challenge) to participate in a warm-up engineering task where they brainstormed as many ways as possible to get a bear to the top of a cliff. Then each small group ranked five of these ideas for a different client (like an egg, a turtle, or a pallet of lumber); this activity was informed by the groupwork strategies book (Cohen & Lotan, 2014) to provide time for students to practice the groupwork norms, arguing, and decision-making with their teammates. For the remainder of the semester, the groupwork norms were displayed on chart paper in the classroom. These groupwork norms were expected to lead to the mediating processes of “using language from/explicit reference of groupwork norms” and “explicitly talking about other peoples’ ideas.”

Task and participant structures

Task and participant structures describe the way the classroom is organized in terms of time, space, materials, people, etc. Though all the choices that go into a classroom experience could be classified as task and participant structures, a conjecture map calls out the salient structures that were intended to influence the mediating processes, and thus, eventually, the desired outcomes. In this teaching experiment, three prominent task and participant structures were considered: “designated time to discuss designs within team and between teams,” “teams of three students,” and “one deliverable per team.”

During the rocket design challenge, we dedicated the entire third day to students discussing within their teams and between teams. Students had access to the rocket prototypes they had already built, but no building materials were brought to the class. We presented them with five tasks for the day, all of which involved discussion with their peers. First, they filled out the decision matrix, then the next design planning worksheet. When groups were finished, we came together as a class to talk about how to give feedback. We provided them with the language “ask, compliment, critique” (Table 3) and let them practice giving feedback on a final design plan that we, the instructors, presented.

Table 3. Guidelines on "how to give feedback" presented to the students.

How to give feedback	Examples
Ask Ask questions to make sure you understand.	How did you decide ____? Could you explain more about ______? What shape are the fins on your rocket?
Compliment When you hear good evidence, say so.	I understand and agree with your thinking. I can see why you chose to use fins.
Critique If you disagree, use evidence to explain why.	I’d make a different decision because ______. “When we used duct tape, our rocket didn’t fly at all.” Our group had a different experience. “Our paper rocket didn’t go as far as our foam rocket.”

After this demonstration, student groups were paired to share their designs and give and receive feedback. We gave students the last few minutes of class to make any revisions to their design plans that came up during the feedback session. During both the decision matrix/next design planning and peer feedback portions of the class, this designated discussion time was expected to foster the mediating processes of “discussion of ideas in relation to decision matrix” and “explicitly talking about other peoples’ ideas.”

For every activity in the semester we had students working in teams of three, which we assigned, paying particular attention to the gender composition in the groups. We wanted to organize students into teams as opposed to pairs because more than two people working together increases the complexity of negotiation required for designing. Due to the simple nature of the design tasks, teams larger than three were ruled out because all students wouldn't be able to participate at the same time in the building and testing process. We aimed for single gender groups (three boys or three girls), and if coed groups were required, we organized them so that they were composed of two girls and one boy. This decision is supported by literature on gender composition in engineering (Tonso, 2006), which generally shows that groups where girls are outnumbered by boys are worse for girls than all-girl or girl-majority groups. Having students work in groups was expected to encourage "explicitly talking about other peoples' ideas" and "all members of a group contribute to one, jointly constructed product."

During the rocket design challenge, we encouraged students to build multiple prototypes, but we required them to have one deliverable per team on the final day. In this way, we privileged both iteration, an important design practice (Crismond & Adams, 2012), and reconciliation through informed decision making, one of the major goals of the teaching experiment. In this teaching experiment, we were interested in the ability of joint construction to both require and mediate discussion amongst students (Roth, 1996). This task structure was expected to require the mediating process "all members of a group contribute to one, jointly constructed product."

Theoretical conjectures: connecting mediating processes and outcomes

Mediating processes are the observable phenomena we expect to see after the implementation of certain embodiments, like tools and materials, discursive practices, and task and participant structures. These mediating processes are hypothesized to bring about certain *outcomes* through *theoretical conjectures*. Outcomes can be related to the dependent variables; they are the things the teaching experiment is intended to produce, like certain learning objectives, attitudes, or interaction patterns. In the case of this teaching experiment, the desired outcomes include: “design iterations informed by reasoning and data”; “a commitment to informing designs with reasoning and data”; “reduced social tension during engineering decision making”; “managing friction in concert with making design decisions”; and “the generation, articulation, and defense of design ideas.” These outcomes capture elements of the goal of this teaching experiment: facilitating collaborative disciplinary decision making in the classroom. I performed a qualitative analysis, reported in Part II, to characterize the student’s work and paint a picture of what collaborative disciplinary decision making could look like in a fourth-grade classroom, including how it may have been supported by the implemented embodiments.

Part II: Comparative case study analysis

While the conjecture mapping tool served to organize the design of the teaching experiment, the comparative case study that I report here combines a discourse analytic approach with methods that originate from grounded theory to analyze student interaction in the classroom as it pertained to the main objective of the teaching experiment: fostering collaborative, disciplinary decision-making. The comparative case study analysis addresses the following research question:

> *What student strategies were part of a productive group’s approach to collaboration in an elementary engineering design challenge?*

Methods

Immediately after each class session, I added to a running document of class notes, including a table with our intended lesson plan on one side and an overview of “what actually happened” on the opposite side. In addition to this comparison, I recorded things that stood out to me and my impressions of each group’s progress during the session. Though we had a general plan for the semester, we planned the details of the next session of the class after debriefing the previous session between me, my advisor, and my co-curriculum developer. In these weekly meetings, we discussed the tools and lesson flows, as well as interesting group dynamics that were emerging. After this meeting, my co-instructor and I wrote the fully detailed lesson plan and created any necessary slides and handouts for students.

After the conclusion of the teaching experiment, I identified the decision matrix and peer-to-peer feedback session as a focus due to the apparent required collaboration and decision making. Karen and I transcribed a group that stood out to us working on the decision matrix and shared this video data and our first impressions with our lab group. Later, I watched the video of all six recorded groups completing the decision matrix and giving each other feedback and wrote a data memo featuring the flow and notable moments from the clips. Through a discussion of this memo with my advisor, I identified two groups as fruitful cases for comparison.

One group had stood out since the beginning of the teaching experiment. The group of three White, female students, Bonnie, Rebekah, and Elena[1], built more rockets than any of the other groups in the class, paid attention to their team dynamics, shared their reasoning with each other and with instructors, and never seemed to struggle with social tensions. Their productivity was salient in the classroom, not only through the sheer volume of prototypes they produced, but also the effectiveness of their prototypes and the strength of their reasoning. Of the seven groups, BRE's target planet, Neptune, was the third farthest away. Their iterations got progressively closer and closer to the target until their seventh prototype reached Neptune. They made changes to their prototypes that were deeply rooted not only in their most recent test, but in other tests of previous rockets, even those built the week prior. Distance was a very prominent requirement to them and they developed reasoning that suggested their rocket needed to be very light to go far

[1] All student names are pseudonyms.

but also heavy to "go down." Their preoccupation with weight as a salient feature of rocket design extended into discussions with instructors, the whole class, and other student groups in the peer-to-peer feedback session. This successive and successful iteration and development of reasoning around rocket design drew attention to this group as especially productive.

Of the five other groups, none were as successful as BRE in collaborative disciplinary decision making. A few of the groups struggled with social tensions and disengaged group members, however one group, Damon (White male), Caroline (Asian female), and Hope (Asian female), stood out as an interesting foil to BRE for a few reasons. For one, they also built a high number of prototypes (five, compared to the seven of BRE). While I was instructing, they seemed by all measures to be a group that worked productively together to create their prototypes. However, upon close review of the video, it became obvious that the ways DCH engaged with each other were less disciplinary and cooperative than BRE. Though members of the DCH team tried to perform metacognitive work about their team dynamics (Caroline) or engage the group in science and engineering reasoning (Damon), these efforts didn't seem to "stick" in the same way they did in the BRE group; bids were made for extended conversation, but they were routinely ignored or rejected.

Once these case groups had been identified, I set to writing data memos for each session of the rocket design challenge, following the same format of flow and notable moments. These memos were generated by watching the video record and referring to transcripts that had been generated by humans through REV, an online transcription service[2]. Through the generation and review of these longitudinal memos, I was able to juxtapose the dynamics of the two focus groups. This comparison exposed three strategies for collaborative disciplinary decision making

[2] See https://www.rev.com/ for more information.

that were successfully employed by the BRE group and either tried and failed or absent from the DCH group. To correct for inaccuracies of the REV transcription, I transcribed exemplar episodes of these strategies (and lack thereof), adding relevant linguistic markers when necessary, and noting nonverbal actions that affected the interpretation of the dialogue. Transcription notations follow the Jefferson system (Jefferson, 2004), Appendix A.

Findings

I identified three strategies of collaborative disciplinary decision making through the juxtaposition of the two case groups. Table 4 presents a summary of the findings of this comparative case study. Each of these strategies is explained in greater detail in the following sections, including episodes of student discourse and excerpts from the decision matrix worksheet or data sheets that exemplify each strategy. In general, BRE demonstrated more stable and shared engagement in these strategies than DCH.

Table 4. Summary of findings.

	Description
Talking about plans	Team members talk about their plans; there is a shared understanding of both the product and the process the team is following. These plans may relate to the design construction, testing procedure, or differing roles and responsibilities among team members. All members of the team are well-versed in the plan. Each member of the team has a general sense of what the others are doing, why, and how all the pieces will fit together.
Responsive discussion	If one student has an idea (about the product or the process), they share that with the group and the group uses the idea as a seed for an discussion. If students disagree, they explain why and take time to come to consensus. Both students who propose and oppose the idea provide reasons for their stances.
Naming	Students decide together on meaningful names for their designs. They use the names to talk about their designs. The name embodies the design ideas and allows the group to do (cognitive) work with the designs as concepts.

Talking about plans

Talking about plans may seem like an obvious strategy, but it should not be taken for granted in any collaborative situations (Lee, Huh, & Reigeluth, 2015). It was a useful strategy particularly when students made plans for not only their design construction, perhaps what we typically think of when we hear the word "plan" in engineering, but also their testing procedure and distribution of work. "Talking about plans" in this case can be something as simple as announcing what you're doing, like "I'm just gonna take this [some tape] off for now" (Rebekah, Rockets Day 2). In this way, the action becomes part of the team discussion and inviting other team members to respond and construct the plan together.

BRE tended to do their planning ahead of time, especially when testing was concerned. The group had a well-defined testing procedure where one girl held the launcher, one stomped on the bladder, and one recorded the test on the data sheet. They rotated these roles and decided beforehand who would occupy each role.

Episode 1, BRE Rockets Day 2

1	Bonnie:	Sure. You go, then I'll go, then Rebekah'll go. I'm the heaviest but Elena has the strongest legs.
2	Elena:	I know, you can hold that.
3	Rebekah:	I'm going after next.
4	Bonnie:	I know.

1	Rebekah:	Elena's supposed to stomp first.
2	Bonnie:	Elena, you can stomp. I'll record.
3	Rebekah:	No you're-- I'm recording. ((pause)) Bonnie, wait! Bonnie, wait!
4	Bonnie:	Got it. Wait, Elena's not ready. Delayed flight, delayed flight, delayed flight, [delayed flight.
5	Rebekah:	[Delayed flight, delayed flight.
6	Bonnie:	Three, two, one.

1	Rebekah:	That was good.
2	Elena:	That was good=
3	Bonnie:	=Yeah
4	Rebekah:	Okay, your turn to record ((*to Bonnie*)) Your turn to record,

Bonnie. ((*Elena picks up the pencil to record*)) No, it's Bonnie's turn to record, your turn to hold. My turn to stomp. ((*they rearrange into the appropriate positions*))

5	Elena:	Wait, is it at the correct angle? Yes, it is. Wait, don't we need to (inaudible) it.
6	Bonnie:	I think it's fine.
7	Rebekah:	I got it ((*as she helps Elena adjust the angle*))

Episode 1 features three excerpts from the testing station; in each, BRE negotiate their roles as holder, stomper, and recorder. This procedure was established on the first day of the rocket design challenge and carried through to every test this team performed.

Rebekah took a lot of responsibility for making the BRE team's processes explicit. While working on the decision matrix, she noticed that Bonnie had completed the top row, accuracy, without consulting the team.

Episode 2, BRE Rockets Day 3

1	Rebekah:	WAIT, we haven't even agreed on that!
2	Bonnie:	I just//
3	Rebekah:	//You just did all these without us!
4	Bonnie:	Fine, I'll erase this
5	Rebekah:	No let's-- wait. Before you erase. ((*reading over what Bonnie Wrote*)) Ok for The Droid, um the accuracy was (.) "1", because it meets requirement. "It fell JUST in the hoop." ((*laughs*))
6	Bonnie:	Because it did
7	Rebekah:	OK, that's a one for The Droid
8	Elena:	Yeah, it does everything it needs to but it could be improved
9	Rebekah:	Okay for the Super Mushroom=
10	Elena:	It got close
11	Rebekah:	=accuracy it got clo:::se but not in it, so it's zero. Same with Mega Hedgehog
12	Bonnie:	Yeah I wrote basically the same thing
13	Rebekah:	Now we're doing repeatability

After being called out, Bonnie offered to erase her work (line 4), an interesting move on her part that may show her willingness to do things together, even though that would require re-doing work she had already done. Rebekah compromised by just reading what Bonnie had written out loud, allowing her and Elena to weigh in on the evaluations. In this way, even though the evaluations weren't performed as a team, they were made explicit in conversation and subject to review by Elena and Rebekah. The next two rows of the decision matrix were completed in this forum style, with one girl writing and the other two supporting or countering her assessments.

In the DCH group, Caroline did a lot of the same work that Rebekah did to get her teammates to think about their process, but where BRE met these proposals with discussion, Hope and Damon largely ignored Caroline's bids. While filling out the decision matrix and next design planning worksheets Caroline implored her teammates: "we have to answer these together guys" (Caroline, Rockets Day 3). On the next day, when they were building their final design, Hope asked Caroline to "tell me when you're done" (Hope, Rockets Day 4) and she replied with a similar bid: "No, guys we're supposed to work together" (Caroline, Rockets Day 4). While discourse markers like "have to" and "supposed to" can be indicative of an authoritarian, or "school-world" framing (Koretsky, Gilbuena, Nolen, Tierney, & Volet, 2014), it is unclear here whether Hope's motivation to work together stems from what she thinks the instructor wants or her own convictions. Regardless, it is striking how resistant her groupmates are to this framing.

Even without Caroline's calling to attention that the DCH group wasn't always doing things together, it was apparent in some of their confusion about their design product. Where BRE did more planning ahead of time, DCH moved through the design challenge and planned as they went. Each of them (or Hope + Caroline and Damon working as sub teams) tended to be responsible for a small piece that they would somehow (usually through a lot of tape) combine at the end. This episode during the building on Rocket Day 2 shows the students navigating planning as they build.

Episode 3, DCH Rockets Day 2

1	Damon:	Here done look! ((*holds the piece he has been building*))
2	Hope:	Wait, what's that supposed to be again?
3	Damon:	The bottom.

4	Hope:	That’s the bottom? It's so big. It's like that ((*gestures length*))
5	Caroline:	Is it gonna be that long? Our cylinder? Our rocket's going to be that long?
6	Hope:	Out rocket's only like this ((*holds up and drops a small tube*))
7	Caroline:	And then, you just tape those parts ((*reaching for Damon’s piece*)) to here ((*the tube Hope has*))
8	Damon:	Yeah, I know.
9	Hope:	We need a cup HERE ((*places her hand at the bottom of her tube*))
10	Damon:	Ours is gonna be really long.
11	Hope:	Don't we need one cup on the bottom? ((*to Caroline*)) We need one cup.
12	Caroline:	Yeah, that's what he's doing.
13	Damon:	One cup’s (inaudible)
14	Hope:	Okay, okay, okay. What do I do now?
15	Caroline:	Glue these as windows. I mean tape them. Tape them with this, so then you can=
16	Hope:	=Okay
17	Caroline:	Should I do this?
18	Hope:	Do what?
19	Caroline:	This ((*holds a cup within a cone she has made*)) ((*no one says anything*))
20	Caroline:	I'm going to do it. I don't know why. I'm just adding things ((*Damon, Caroline, and Hope each build their own thing*))

This episode begins with Damon announcing that he has completed his piece of the rocket. Hope expressed some confusion about what he’s done, and both she and Caroline revealed that they didn’t think the rocket would be very long. This highlights some of the issues with not planning ahead; there was not a unified concept of the total rocket, just individual conceptions of different pieces. Caroline reconciled her confusion, making a plan for connecting Damon and Hope’s pieces (line 7). Damon seemed to indicate that he thought this was the plan all along (line 8). In lines 9-16, Hope directed questions about the product to Caroline, who illuminated more of the plan: “that’s what he’s doing” (line 12). In 17-20, Caroline tried to get input from Hope about her piece but was ignored. Before they returned to each building their own thing, Caroline noted that she doesn’t know *why* she’s doing what she’s doing, she’s “just adding things” (line 20). This was not the only time Caroline brought her uncertainty about their plans to the conversation.

On the first day of the rocket design challenge, in response to Damon saying, “everyone is better than us,” Caroline said, “Yeah because we’re not thinking through.” This specifies that she associated successful teams with thinking through plans.

Planning ahead and working together also contributed to the students’ sense of shared understanding of their product. In Episode 4 below, Caroline acknowledges that the fragmented nature of their group served to unevenly distribute both the work load and the understanding of the design. While building their final prototype, Hope and Caroline were both at a loss for what to do, which Caroline attributed to Damon’s dominating the building process (line 2).

Episode 4, DCH Rockets Day 4

1	Hope:	What do I do?
2	Caroline:	You don't know what to do because he's doing all the work and we have no idea what you're trying
3	Hope:	What am I gonna do??
4	Caroline:	I don’t know. What are we doing in here?

Whether or not students had a shared understanding of their designs became most apparent when the instructors visited the groups. Bonnie, Rebekah, and Elena were able to engage equally with the instructor, often riffing off each other to explain the current state of affairs.

Episode 5, BRE Rockets Day 3

1	Nicole:	Okay, so I'm interesting about how you guys interpreted this ((*the decision matrix*)). So your criteria was weight, but then you were judging it based on how far it went?
2	Bonnie:	Right, because if it was heavier, it might've gone-somewhere
3	Rebekah:	Because the heavier it was - it would go slower, and drag it down.
4	Bonnie:	But it could have been for pressure. It could have been for pressure, too. Elena was our best stomper, so some of these could've been (helped) by her stomping, but some of them could've been somebody else was good.
5	Elena:	'Cause we found out that the heavier it was, the less far it went.
6	Nicole:	Okay.

In this episode, Bonnie, Rebekah, and Elena each shared some evidence or reasoning with Nicole about how far their prototypes went with respect to weight, the criterion they had decided on for the last row of the decision matrix. This demonstrated their shared understanding of their design concept, standing in stark contrast to the way DCH often interacted with the instructors. In a check-in with Ryan on the last day of the design challenge, Damon and Hope told him that they were done, but this seems like news to Caroline, who disagreed.

Episode 6, DCH Rockets Day 4

1	Ryan:	Are you guys done with your design?
2	Hope:	[Yeah.
3	Damon:	[Yeah.
4	Caroline:	Reallyy??
5	Ryan:	((*to Caroline*)) Do you not think it's done?
6	Caroline:	I do NOT think it's done at all.
7	Ryan:	What else do you think could be done?
8	Damon:	Stop it. ((*to Hope, who is messing with their rocket*))
9	Hope:	No, I'm fixing it.
10	Damon:	((*to Ryan*)) We don’t need wings! Wings are for birdies.

It was typical of check-ins between an instructor and the DCH group to turn into some members of the group talking to the instructor only, and not each other. In Episode 6, Ryan tried to engage Caroline (lines 5 and 7) in sharing what she felt was incomplete. She had been proposing that they add wings to the rocket and had even made a pair of foam wings to attach. Damon was aware that she wanted to do this, and he took line 10 as an opportunity to reject her idea while directing his talk to Ryan, effectively answering Ryan’s question to Caroline from line 7 for her.

Responsive discussion

This strategy involved group members treating ideas as proposals for discussion and doing discursive work to come to consensus based on provided reasoning. This engagement was a key strategy that contributed to BRE’s successful collaboration; generally, proposals in this group were met with discussion.

Episode 7, BRE Rockets Day 2

1	Elena:	I haz idea, I haz idea! What if I cut a circle and I put it on top of there just to add a little more weight? Right? Can I do that?

2	Rebekah:	Sure
3	Elena:	I'm gonna do that. I think that might work because we need like a little more weight on this thing.
4	Bonnie:	You're gonna make it heavier? It might not be heavy enough, I don't know.
5	Rebekah:	No, these might work.
6	Elena:	Yeah.

Episode 7 is an illustrative example where Elena introduced an idea (“put it [a circle] on top”) with reasoning (“to add a little more weight”) and asked her groupmates for approval. Rebekah agreed with her (line 2), and Elena continued to justify her idea, claiming it “might work” because they “need a little more weight.” Bonnie asked a clarifying question but then admitted she doesn’t know what’s best. Rebekah agreed with Elena’s idea (line 5) and Elena signaled their consensus to proceed with her idea (“Yeah,” 6).

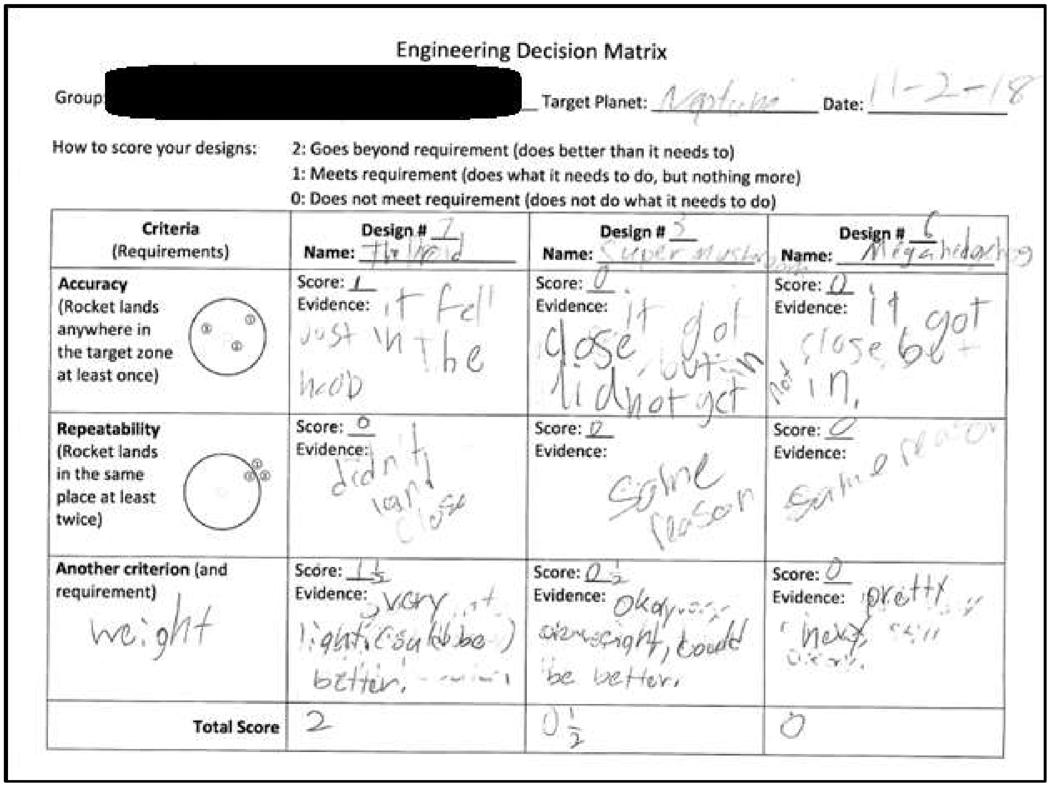
In Episode 8, they follow a similar pattern of someone introducing a topic and all three group members contributing to the discussion with reasoning. This example is interesting because Rebekah opened the conversation not with a new idea, but with a question about their design process. They had just finished testing a prototype, and Rebekah invites them to talk about what their next steps will be.

Episode 8, BRE Rockets Day 2

1	Rebekah:	Okay. What do we think we need to improve on?
2	Bonnie:	I think it needs to be a little lighter.
3	Elena:	Same. Maybe we can take off like one of the popsicle sticks.
4	Bonnie:	I don't think we need these [wings.
5	Rebekah:	[No, the duct tape.
6	Elena:	The duct tape! That's gotta be it.
7	Bonnie:	And we gotta make the wings a bit smaller. Let's make the wings a bit smaller.
8	Rebekah:	I don't think the wings are actually the problem.
9	Bonnie:	Right, but they're a little heavy. They're a little heavy and a little bit might stop it. It might have reached. Let's make it shorter
10	Rebekah:	Guys, I'm gonna deconstruct most of this to get to the duct tape.

Bonnie and Elena both responded with ideas about how to improve their rocket, building off each other; Bonnie made a broad suggestion, making the rocket lighter (line 2), and Elena proposed one way to do that: remove one of the popsicle sticks (line 3). Bonnie suggested another thing they could remove to reduce weight (lines 4), wings, and Rebekah jumped in, proposing the duct tape as a source of weight. Elena seconded that the duct tape is heavy and could be removed (line 6). Bonnie brought the conversation back to the wings, proposing making the wings smaller as opposed to removing them completely (line 7) and reinforcing her reasoning that the weight of the wings could have been preventing a successful launch ("it might have reached," line 9). Though Rebekah went ahead with the idea to remove the duct tape, it's interesting to note that after testing the slightly lighter iteration that came out of this discussion, they did end up making the wings smaller, then eventually removing them altogether. This example really captures the responsive nature of this strategy; these students heard each other's ideas and their reasons and responded to them with even more fodder for conversation.

In addition to discussing their rocket performance and build strategies, the BRE group discussed alternative interpretations of the decision matrix worksheet. In Episode 9, Elena is writing in the final row of the decision matrix, evaluating each of their designs based on a criterion they devised, "weight." She proposed assigning a score of one half, though the decision matrix recommends scores of 0, 1, or 2. Bonnie and Rebekah initially did not agree, but they engaged in the conversation, hearing Elena out and eventually employing her proposed half scores, shown on their completed decision matrix (Figure 10).



Engineering Decision Matrix

Group [redacted] Target Planet: Neptune Date: 11-2-18

How to score your designs: 2: Goes beyond requirement (does better than it needs to)
1: Meets requirement (does what it needs to do, but nothing more)
0: Does not meet requirement (does not do what it needs to do)

Criteria (Requirements)	Design # 7 Name: [illegible]	Design # 3 Name: [illegible]	Design # 6 Name: [illegible]
Accuracy (Rocket lands anywhere in the target zone at least once)	Score: 1 Evidence: it fell just in the hoop	Score: 0 Evidence: it got close but it did not get in	Score: 0 Evidence: it got close but not in.
Repeatability (Rocket lands in the same place at least twice)	Score: 0 Evidence: didn't land close	Score: 0 Evidence: same reason	Score: 0 Evidence: same reason
Another criterion (and requirement) weight	Score: 1½ Evidence: very light (could be) better.	Score: 0½ Evidence: okay weight, could be better.	Score: 0 Evidence: pretty heavy
Total Score	2	0½	0

Figure 10. BRE Decision matrix worksheet.

Episode 9, BRE Rockets Day 3

1	Elena:	Um. (What should we give this?) Let's give it a zero. Uh, I'll give it a zero, because it didn't make it, but it got (close)
2	Rebekah:	No.
3	Elena:	How about zero and a half, because it got close?
4	Rebekah:	That's not one of them ((*an allowed score*)).
5	Elena:	Cuz like it's kind of like stuck in the middle like it doesn't really
6	Rebekah:	Let's do zero question mark 1
7	Bonnie:	Umm don't know because it's not exactly
8	Elena:	I think zero and a half is fine
9	Rebekah:	All of them are-- these two are both zero and a half
10	Elena:	Cuz it didn't make it but it got decently close.
11	Bonnie:	It did.
12	Elena:	So it wouldn't be a complete zero. But it also wouldn't be a one.

Early in this discussion, Rebekah was very opposed to the "1/2" idea (lines 2, 4). Elena asserted her position, trying to give the rockets credit for getting close, or "stuck in the middle" (lines 1, 3, 5). Rebekah negated this first by referring to what was given, the scores outlined on the decision matrix worksheet (line 4), then by proposing an alternative ("zero question mark 1") that incorporated the sanctioned scores, but also captured that the evaluation was somewhere between those scores. Bonnie started to disagree (line 7), but Elena asserted her position (line 8) and Rebekah seconded the new scoring paradigm (line 9). Elena continued to explain her reasons, to which Bonnie seems to acquiesce in line 11.

Whereas in BRE proposals were met with discussion, in the DCH group, proposals for design ideas or course of action were often rejected or ignored. In Episode 10, Caroline wants her team to consider filling out the data sheet as part of the build process, which Hope seems to agree with, but Damon presents his strong opinions without explaining why.

Episode 10, DCH Rockets Day 1

1	Caroline:	Wait shouldn't we be drawing what it looks like?=
2	Damon:	=No, not yet not yet! When we're finished.
3	Hope:	Now we have to duct tape the paper.
4	Caroline:	We didn't write anything on here= ((*pointing to data sheet*))
5	Hope:	=Maybe we should.
6	Damon:	No, not yet. Not until we're done.
7	Caroline:	Are you sur:e I thought we were supposed to do it first and then we start writing it and then we start like… ((*she peters off, holding the bottom of the rocket while Damon continues working on the top*))

Caroline initiated the conversation with a fairly open question, posing her conception of what their design process should be as a clarification ("shouldn't we…"). Damon insisted "not yet," not until they're finished, the stance he occupied for the entire conversation (lines 2 and 6). In her last turn, Caroline envisioned a course of action where they would have drawn and described their design before building it, but she lost steam and dropped the issue, resigned to filling out the form later (line 7).

Caroline took over most of the documentation for DCH, and by the end of the design challenge, she grew bitter in her role and, on Rockets Day 3, as they neared completion of the decision matrix, expressed her dissatisfaction with her groupmates' behavior and lack of help.

Episode 11, DCH Rockets Day 3

1	Caroline:	Guys! You need to do this with me Damon stop (inaudible) DAMON stop doing that ((*puts her hand over her face*)) Damon can you stop. DAMON. ((*Damon messing with the camera, with the rockets*)) He's putting his face up to the camera. Just please don't do that. ((*She writes on one of the worksheets for two minutes while Damon and Hope fool around.*))
2	Damon:	Can you do this? Can you do this? ((*juggles rocket*))
3	Damon:	Let's just add on to this. ((*throws rocket*))
4	Damon:	This is the best rocket (inaudible)
5	Damon:	A million people are in this part
6	Caroline:	GUYS ARGH you need to pay attention. You know we're done with this paper now. ((*Hope and Damon ignore her*.))
7	Caroline:	Even if we finish this paper it's NOT time to fool around ((*Damon and Hope continue to fool around*.))

In her opening turn, Caroline voiced an idea about their design process, that her groupmates "need to do this" with her (line 1). She pleaded Damon to stop fooling around and help her, but when it proved useless, she gave up and completed the form on her own ("we're done with this paper now," line 6). This statement was ignored, and she expressed another idea about how their time should be structured, claiming "even if we finish this paper it's NOT time to fool around" (line 7).

While Caroline's frequent attention to process was often rejected or ignored, Damon's attentions to their rocket *design* were similarly rejected or ignored. In this brief episode of rejection, Hope immediately shuts down one of Damon's design ideas, leaving no room for discussion (Episode 12).

Episode 12, DCH Rockets Day 2

1	Damon:	Guys guys guys, I have a good idea, let's do these. Like, stack cups on top, cups on bottom.
2	Hope:	No. ((*she points at something Damon has drawn or written*)) We're not doing that. We're not doing tha:::t! We're not doing tha::t. ((*groans*))

This attitude towards ideas, as well as explicit design process plans like in the following episode, served to fragment the DCH group.

Episode 13, DCH Rockets Day 2

1	Caroline:	Wait wait wait, we should start with the paper and then put the foam around it. To like shape the paper.
2	Hope:	No I think we could make—((*reaches for the paper Caroline is Holding*)) Roll this up. Caroline, I think we should roll the paper up like this, and then we can wrap it around the foams.
3	Damon:	No, let’s, let's wrap the rocket around with this ((*holding up a cone and a popsicle stick*))
4	Hope:	No! ((*turns back to Caroline*))
5	Damon:	So then, more air pressure can come in and make the rocket go further.
6	Hope:	But, you do yours. Me and Caroline, we're gonna do- we’re gonna- we’re gonna--
7	Caroline:	You do what your idea is, we'll try to make the bottom of the rocket, you’ll try to make the top.
8	Hope:	Yeah we'll make the bottom!

Caroline and Hope began this episode acting as a pair, brainstorming together. When Damon jumped in with his own idea (line 3), he was rejected, verbally and physically, by Hope (line 4). He steamed ahead, trying to justify his idea with some scientific reasoning about air pressure (line 5). Hope and Caroline then laid out a plan where they would work as a pair on one half of the rocket, and he could do his idea for the top of the rocket. By resorting to a “division of labor” approach, as opposed to consensus like BRE, DCH effectively fragmented their rocket concept. Though this strategy is often employed in the higher levels of engineering, where projects and teams are large, it did a disservice to this team as they sacrificed a shared understanding of the product they were creating.

Naming

Naming was a productive strategy when student teams decided together on meaningful names for their designs and used the names to talk to each other, instructors, and other students about their designs. The BRE group stood out for the naming conventions they developed. Each of the seven[3] prototypes this group created was documented on a data sheet with the corresponding name written at the top. These design names and numbers are organized in Figure 11. Versioning was built into BRE's naming scheme; for instance, their third rocket was named "Super Mushroom[4]" because it was a minor variation on their second design, "Mushroom."

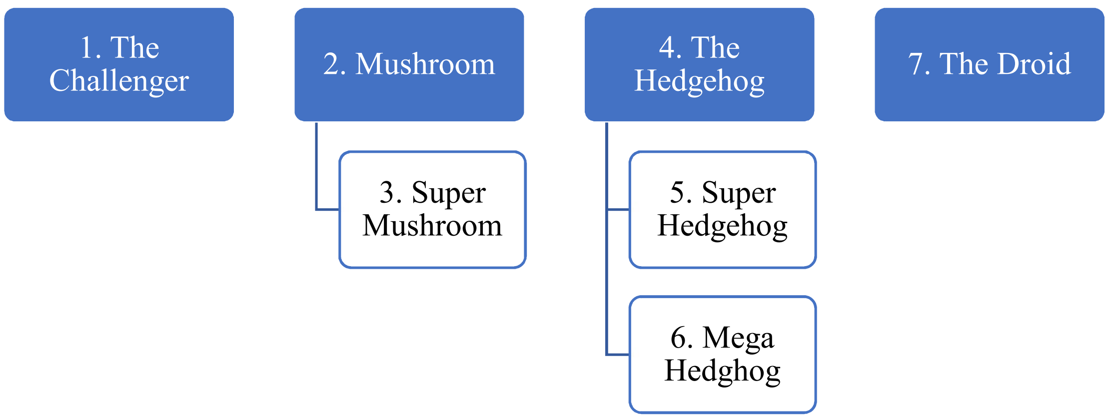


Figure 11. *Hierarchy of BRE designs. Numbers indicate the order in which the prototypes were constructed.*

They carried this naming convention into their fourth, fifth, and sixth prototypes. This effectively gave these students self-selected language to describe their iterative process. This was evident on their data sheets; they described their fourth prototype, The Hedgehog, as "super mushroom with wings and popsicle sticks." This change was deemed significant enough to create a new class of rockets: "hedgehog." When describing the later versions of the Hedgehog rockets, they included descriptions like "hedgehog, lighter" (Design 5, Super Hedgehog data

[3] BRE built and tested the most prototypes of any group (7) followed by DCH (5) and the rest of the groups (4, 3, or 1).

[4] Official prototype names assigned by the students on the data sheets are reported in capitals. In quotations, this refers to the *name* of the prototype; out of quotes, this refers to the physical prototype.

sheet) and "super hedgehog but smaller" (Design 6, Mega Hedgehog data sheet). This demonstrates how these students were able to attach an entire prototype, including how it looked, was built, and performed, to one or two words. This embodiment of an entire design concept with a name enabled Bonnie, while planning their final prototype, to tell her teammates "the final design will be a cross between this one ((*points to "The Droid" on the decision matrix*)) and the Super Mushroom." The members of BRE considered these names to be such an integral part of their prototypes that they used them in conversation amongst themselves, instructors, groups within the class, and students outside of class. For instance, on the first day of the rocket challenge as they were testing a prototype in the hallway, a student from another class passed through and asked what they were doing, to which Bonnie replied, "we're testing Super Mushroom is what we're doing." Even though this student had absolutely no context for this comment, it seems that the name was so salient and encapsulating of their design to Bonnie that she couldn't help but use it.

This encapsulating feature of prototype names potentially stemmed from the way the name captured something physical about the designs. Episode 14 features BRE coming to the decision to call their seventh prototype "The Droid." Rebekah made a bid to name it "the squid," (line 1) and Elena countered with "storm trooper," (line 2) citing resemblance. Bonnie agreed, and Rebekah jumped on board. Seconds later, after she had continued working on it, she exclaimed that it looks like R2D2 and should be named "the droid" (line 10); Bonnie seconded this with robot noises ("beep boop beep," line 11).

Episode 14, BRE Rockets Day 2

1	Rebekah:	What if we call this the squid?
2	Elena:	It looks like a storm trooper.
3	Bonnie:	Same.
4	Rebekah:	The what?
5	B and E:	Storm trooper.

6	Rebekah:	Oh, yeah, the storm trooper, that's a great one.
		…
7	Rebekah:	No, it's the droid! The droid! It looks like R2D2, we're gonna make it look like R2D2!
8	Elena:	What if I cut this?
9	Bonnie:	What do you mean, lock it?
10	Rebekah:	Okay, it's gonna be called The Droid rocket.
11	Bonnie:	Beep boop beep.

In this example, the three students contributed enthusiastically to name their design, relying on a descriptive naming scheme ("looks like"). This vein of reasoning worked both ways for this group; The Mushroom was aptly named because "it looks like a mushroom" (Elena, Rockets Day 1), and brown foam was used for The Hedgehog to enhance resemblance ("that's why I got brown," Bonnie, Rockets Day 1). The Challenger was named in honor of its status as their first prototype, "because it's gonna challenge" (Bonnie, Rockets Day 1).

Names in BRE were chosen collaboratively; one group member posed a name as a question to the rest of the group and alternatives were offered until agreement was achieved. This is evident in Episode 14, and Episode 15 provides another example of Elena proposing a name, "the hedgehog two," followed by a team discussion.

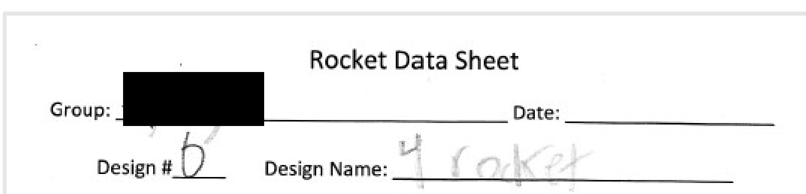
Episode 15, BRE Rockets Day 2

1	Elena:	How about we just call this the hedgehog two?
2	Bonnie:	No, we need a name better than the hedgehog two
3	Rebekah:	Nooo the super hedgehog!
4	Bonnie:	Super hedgehog, yeah!
5	Elena:	Will it work, Super Hedgehog? ((*addressing prototype*))

After Elena's initial proposal, Bonnie created the need for discussion by not agreeing; Rebekah used this opening to propose her own name idea ("super hedgehog"). Bonnie agreed, and Elena closed the issue by adopting the name "Super Hedgehog" and using it to address the prototype.

Throughout the course of the design challenge, BRE referenced "The Snow Leopard," an idea for a rocket name that they reserved for their best design, something that was decided before the camera started rolling on the first day of rockets. They referred to this coveted name almost like a trophy, with Elena reminding them on the last day of the challenge, "we all agreed that our best design would be called 'the snow leopard.'" On this same day they opt to name their eighth and final design "Anonymous" because, until they test it, they wouldn't know if it were the Snow Leopard. They even talk about renaming The Droid (their best prototype from the first two days) to the Snow Leopard should Anonymous not do as well. "The Snow Leopard" was a name that held meaning for the group in terms of rocket performance and could be worn like a crown by any rocket that earned it. Their willingness to rename rockets is further evidence that their design concepts were fully solidified with the names serving as common reference among the group members.

DCH stands in stark contrast to this prolific use of names in the BRE group. We collected five completed data sheets from the DCH group, four of which had design names filled in. The information on these data sheets was inconsistent and unreliable; for instance, one data sheet listed the design number as "6" and the design name as "4 rocket" (Figure 12), a source of confusion for analysts and the students alike.


Rocket Data Sheet

Group: [redacted] Date:

Design # 6 Design Name: 4 rocket

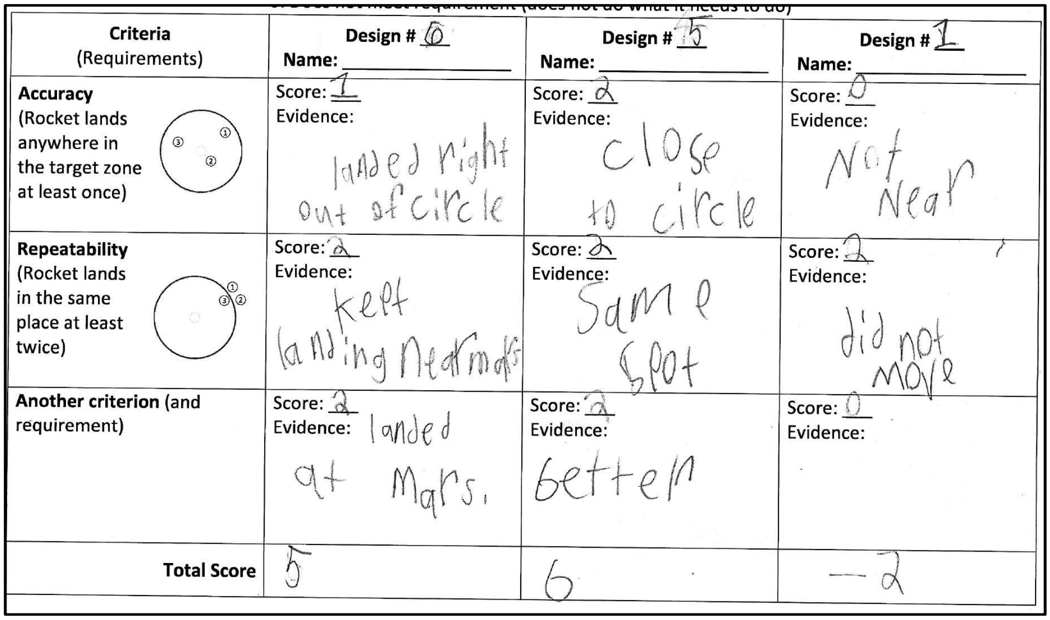
Figure 12. *DCH data sheet showing confusing, potentially conflicting, information.*

This discrepancy caused trouble for DCH while trying to complete the decision matrix, which required looking back over the data sheets to evaluate three of their prototypes. They had difficulty identifying which of the physical prototypes corresponded to which data sheets (Episode 16).

Episode 16, DCH Decision Matrix Day

1	Hope:	Wait what's this one? ((*points to the data sheet of the best prototype*)) Was it this one? ((*holds up a rocket prototype*))
2	Damon:	Yeah that ((*the rocket Hope is holding*)) was that one
3	Hope:	This one? ((*shaking the prototype*))
4	Caroline:	Yeah
5	Hope:	Okay
6	Caroline:	That was design five, just say five. I don't remember.
7	Hope:	Okay so
8	Damon:	That was actually design six. That wa-- I already did that one
9	Hope:	Okay! ((*laughs*)) It's this one! ((*holds up the same prototype*))
10	Damon:	That was design four

Just before this episode began, Caroline and Hope identified the data sheet of their most successful prototype (Figure 12). Hope then tried to find the corresponding physical artifact, and Damon confirmed that the one she had chosen matched the data sheet they identified. Caroline proposed calling it "design five," (line 6) acknowledging that she didn't remember the design number (though "6" is written on the sheet). Damon then proposed that it was both design six (line 8) and design four (line 10), which, though consistent with the two numbers that are written on the data sheet, is not aligned with conventional design numbering where prototypes would be numbered chronologically in the order they were produced. DCH's decision matrix (Figure 13) shows that they evaluated designs 6, 5, and 1, but you can also see that numbers were written previously then erased.



Criteria (Requirements)	Design # 6 Name:	Design # 5 Name:	Design # 1 Name:
Accuracy (Rocket lands anywhere in the target zone at least once)	Score: 1 Evidence: landed right out of circle	Score: 2 Evidence: close to circle	Score: 0 Evidence: Not Near
Repeatability (Rocket lands in the same place at least twice)	Score: 2 Evidence: kept landing Nearmars	Score: 2 Evidence: same spot	Score: 2 Evidence: did not move
Another criterion (and requirement)	Score: 2 Evidence: landed at Mars.	Score: 2 Evidence: better	Score: 0 Evidence:
Total Score	5	6	−2

Figure 13. DCH decision matrix worksheet.

In addition to confusion about design numbers, the decision matrix (Figure 13) also shows that the students identified prototypes only by design number, not design name, though most of their data sheets did have design names written. For the most part, one student dominated these naming decisions, and no obvious verbal agreement was reached. The naming of DCH's first prototype, "Rocket Number 1," is represented in Episode 17.

Episode 17, DCH Build Day 1

1	Damon:	What should the design be named? ((*to J and E, then turns to the data sheet to write*)) Rocket…
2	Hope:	Rocket what?
3	Damon:	((*writing*)) Rocket number one
4	Hope:	Rocket hundred! ((*laughs*))
5	Damon:	((*sits up from writing*)) It's called rocket number one.
6	Caroline:	Hashtag rocket number one!
7	Damon:	No. Rocket name is just rocket number one.
8	Caroline:	((*reaches for the data sheet, Damon grabs it and turns away*)) That has to have hashtag!
9	Damon:	((*blows raspberry at Caroline*))

Much like BRE, this naming conversation begins with one student, Damon, posing a question to the group (line 1). Before the other two could offer suggestions, he began writing his idea, "Rocket number one" (line 3). Hope jokingly made a suggestion (line 4), which was rejected (line 5), and Caroline's excited suggestion "hashtag rocket number one" (line 6) was met with disapproval and even ridicule (the raspberry in line 9). On the second day of building, when they began their second prototype, Caroline tried to stimulate a group conversation, saying to the group "Our name for the rocket will be Rocket 2. Rocket 2. Do you want the rocket to be Rocket 2?" (Rockets Day 2). She was completely ignored by Hope and Damon, left to make the naming decision on her own. Two other prototypes had names recorded on their data sheets, "Mr. Rocket" and "Mrs. Rocket," but these names were never decided on as a group and never appeared in group conversations about the rockets. This, plus Caroline's hard work on the data sheets, indicates that after the first day of the rocket design challenge, she took naming decisions into her own hands.

On Rockets Day 2, Caroline and Hope began comparing their designs, reviewing and evaluating rocket performance from data sheets with comments like "this one didn't go at all," "that one was good," and "yeah that was a fail." In all of these examples, the students were looking at data sheets that had names on them, but not using the names. This may seem unsurprising, considering that the artifact (the data sheet) was occupying their shared attention; however, compared with the prolific usage of names in BRE group conversations, this was strikingly sparse.

Additionally, the names that were discussed in the DCH group bore no resemblance or significance to the prototypes themselves. "Rocket 1" and "Rocket 2" capture chronological information, but said nothing about how the rockets looked, worked, or what they were inspired by. Other names recorded on data sheets were "Mr. Rocket" and "Mrs. Rocket," which were more removed from chronological information, but didn't appear to hold any additional information about the design process. These names were not an object of the team's discourse at any point, generated solely by Caroline as she completed the documentation for her group.

Discussion

The findings presented for the comparative case study address the question *What student strategies were part of a productive group's approach to collaboration in an elementary engineering design challenge?* I observed three such strategies: talking about plans, responsive discussion, and naming. Success in talking about plans and naming hinged on responsive discussion; without the time for and commitment to discussion, effective strategies like naming and talking about plans could not become fully stable. As part of the design of the teaching experiment, we provided time for discussion, both within groups and between groups in the peer-to-peer feedback session. However, the juxtaposition of BRE and DCH illustrates that time is necessary but not sufficient for productive discussion to ensue. A shared valuing of other students' ideas and propositions was necessary for a bid to progress into a discussion and, eventually, consensus. Roth found similar results in his studies of elementary student problem solving in engineering: "For a shared problem, solution, or course of action to emerge several individuals had to agree on a common set of relationships between the (arte)facts, events, and discourse to which they were attuned" (Roth, 1996). This common set of relationships could not be established in the DCH group, where rejecting or ignoring proposals was common. This is consistent with findings from Barron in group mathematical problem-solving where "groups that did well engaged the ideas of participants, had low rates of ignoring or rejecting, paid attention to attention, and echoed the ideas of one another" (Barron, 2003).

When students engaged in responsive discussion, they were able to cooperate to reach consensus about ideas and develop shared understandings. Students in the BRE group encapsulated their shared understanding of a design concept with a name, an emergent phenomenon that was truly unique in the class. In addition to uniqueness, the way that Bonnie, Rebekah, and Elena were able to refer to an entire design idea with a word or two was incredibly *useful* as they communicated with each other. Though other student groups named their designs, none developed a naming scheme that incorporated iterative versioning or operated on their designs at such an abstract level. Other disciplines, notably math education, have alluded to the effectiveness of naming novel ideas in order to allow students to do cognitive work with them (Ball, 1993). In her work with "Sean's numbers," Ball names an unconventional mathematical idea after a student both to demonstrate the value of his idea and to give the class another concept to engage in mathematical practices with, like looking for patterns. The moments where BRE described their final design as "a cross between this one [*points to "The Droid" on the decision matrix*] and the Super Mushroom" or wrote on their data sheet descriptions "hedgehog, lighter" demonstrated how useful these abstract, verbal shortcuts were; they were able to sidestep relying on holding the physical prototype like other groups because they could hold design planning discussions using only the names.

As demonstrated by the example of "The Snow Leopard," BRE's abstraction went beyond the physical prototypes they created. In the case of the Snow Leopard, the name exists on such an abstract level that it belonged to any prototype which performed the best. This allowed them to use the concept of the Snow Leopard to state predictions. For instance, on their first day, Bonnie described an idea for a prototype then said, "AKA the snow leopard," essentially making a prediction that her idea, when built and tested, would perform the best. Their willingness to hold off on assigning a name (in the case of Anonymous) or to consider renaming prototypes they had already tested (in the case of The Droid) showcases both the power of naming and the strength of this groups' abstract conception of designs. It is possible that the data sheets and decision matrix contributed to this sense of each design as a concept. The data sheet allowed them to keep a precise record of each iteration, including how it looked and how it performed. In BRE, all this information became attached to the name at the top of the sheet. Because the decision matrix had students put design concepts side by side for comparison, it focused attention on designs as "things," setting them up to refer to distinct designs on the same worksheet, with room to transfer the design number and name information from the data sheet to the decision matrix.

BRE employed the strategies of talking about plans, responsive discussion, and naming toward their productive engineering. Their evidence-based iteration was built into their naming scheme and emerged through stable engagement in talking about plans and responsive discussion. The shared understanding of design concepts that they built through these mechanisms contributed to their ability to make well-informed changes and reflect on whether they were successful. In DCH, where ignoring and rejecting proposals was common and led to fragmentation of documentation, construction, and design concepts, their engineering work suffered. Though they built many prototypes, their changes were not informed by the results of testing their prototypes. For example, the first rocket prototype they constructed with the "divide and conquer" method took the entire first day of building and ended up being a leviathan of duct tape, foam, and popsicle sticks (Figure 14b). When they tried to test it, it could not even get off the stand. Their next prototype (not pictured) was also constructed with the divide-and-conquer method and was, again, two large constructions taped together that didn't launch. In this way, not stably engaging in discussion with each other and working in sub teams was detrimental to

DCH's engineering. Only being exposed to other groups' approaches in the peer-to-peer feedback session did they decide to make a smaller rocket (Figure 14a).

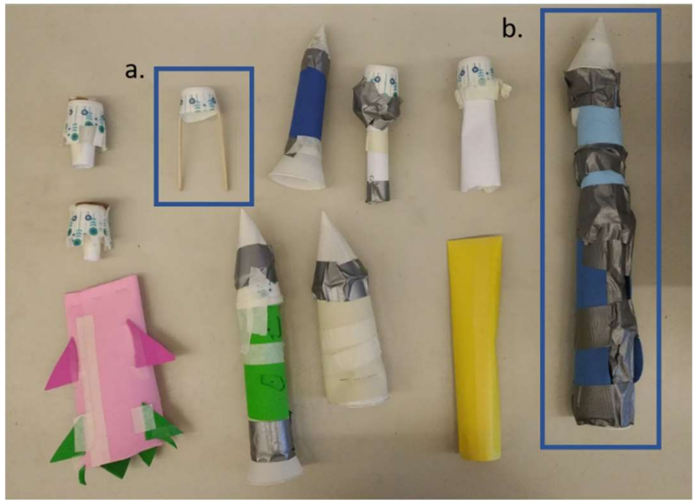


Figure 14. Rockets from the class, highlighting a) DCH's final rocket prototype and b) DCH's initial prototype.

These findings continually point to the importance of responsive discussion in the classroom. In order for this discussion to occur, all students in a group needed to share the values of being open to hearing and responding to ideas from others. We had envisioned the groupwork norms fostering these values, but the current implementation proved to not be enough. Though BRE seemed to share these values, it's impossible to say how much of that came from the embodiments and how much came from their already established relationships. In this implementation, the groupwork norms were minimally emphasized. Though discussed on the first day of class and posted at the front of the room, they were rarely referenced by instructors and students. Conducting this teaching experiment within an outreach context, where we were only with the students for one hour per week, was not ideal for establishing engineering groupwork norms. In future iterations of the teaching experiment, much more practice and modeling could help students adopt these norms, potentially helping them value shared understanding with their teammates.

Conclusions and Implications

In this thesis, I described the design of a teaching experiment as well as the observed student strategies that fostered collaborative, disciplinary decision-making in an elementary engineering classroom. Through the conjecture mapping technique, I explained how the teaching experiment was expected to lead to certain outcomes; the comparative case study provided insight into the ways that children, novice students who have not been indoctrinated in the same ways as traditional college students, engage in engineering. I was able to characterize three effective strategies that students employed in service of their collaborative engineering work: talking about plans, responsive discussion, and naming. Evaluating these findings in light of the conjecture map reveals some key failures of the implemented embodiments to bring about the proposed mediating processes, as well as a lack of what proved to be a key mediating process: discussion. Though many of the theoretical conjectures were realized for the BRE group, it cannot be claimed that this came from the embodiments of the teaching experiment. While the DCH group received the same scaffolds and made bids to plan, discuss, and work together, I did not observe the same level of stable engagement in the strategies of talking about plans, responsive discussion, and naming that were productive for the BRE group. The worksheets, groupwork norms, time for discussion, and working in teams towards one final deliverable was sufficient support for BRE and led to the discussion that facilitated the desired outcomes. DCH seemed to require more support to work together on a single, cohesive design and hear other team members' suggestions, especially when they contained science or engineering reasoning. Future iterations of this curricular design should examine other ways of reinforcing the groupwork norms, more instructor support for the use of naming in the classroom, and more specific scaffolds for engaging in discussion.

Appendix A: Jefferson transcription notation

(.)	A full stop inside brackets denotes a micro pause, a notable pause but of no significant length.
(0.2)	A number inside brackets denotes a timed pause. This is a pause long enough to time and subsequently show in transcription.
[	Square brackets denote a point where overlapping speech occurs.
> <	Arrows surrounding talk like these show that the pace of the speech has quickened.
< >	Arrows in this direction show that the pace of the speech has slowed down.
( )	Where there is space between brackets denotes that the words spoken here were too unclear to transcribe.
(( ))	Where double brackets appear with a description inserted denotes some contextual information where no symbol of representation was available.
Underline	Where a word or part of a word in underlined denotes a raise in volume or emphasis.
↑	When an upward arrow appears it means there is a rise in intonation.
↓	When a downward arrow appears it means there is a drop in intonation.
→	An arrow like this denotes a particular sentence of interest to the analyst.
CAPITALS	Where capital letters appear it denotes that something was said loudly or even shouted.
Hum(h)our	When a bracketed 'h' appears it means that there was laughter within the talk.
=	The equal sign represents latched speech, a continuation of talk.
::	Colons appear to represent elongated speech, a stretched sound.

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