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Math, Science, and Engineering Integration in a High School Engineering Course: A Qualitative Study

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Abstract

Engineering in K-12 classrooms has been receiving expanding emphasis in the United States. The integration of science, mathematics, and engineering is a benefit and goal of K-12 engineering; however, current empirical research on the efficacy of K-12 science, mathematics, and engineering integration is limited. This study adds to this growing field, using discourse analysis techniques to examine whether and why students integrate math and science concepts into their engineering design work. The study focuses on student work during a unit from a high school engineering course. Video data were collected during the unit and were used to identify episodes of students discussing math and science concepts. Using discourse analysis, the authors found that students successfully applied math and science concepts to their engineering design work without teacher prompting when the concepts were familiar. However, explicit teacher prompting and instruction regarding the integration of less familiar concepts did not seem to facilitate student use of those concepts. Possible explanations and implications are discussed.

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Introduction

Engineering in K-12 classrooms has been receiving expanding emphasis in the United States as evidenced by the rising number of K-12 engineering courses, new K-12 engineering curricula, a growing field of educational research on the topic, and the *Journal of Pre-College Engineering Education*, a journal dedicated to the subject (http://docs.lib.purdue.edu/jpeer/). Nationwide, public high schools are offering engineering courses, and many K-12 classes are infusing engineering content into their traditional mathematics and science courses. In fact, 41 states have engineering skills and knowledge embedded in their science, technology, or mathematics standards (Carr, Bennett, & Strobel, 2012). In addition, the Next Generation Science Standards identifies engineering standards for each grade level from kindergarten to twelfth grade (NGSS Lead States, 2013).

This integration of science, mathematics, and engineering is a recurring theme when describing the benefits and educative goals of K-12 engineering. The National Research Council puts "improved learning and achievement in science and mathematics" (p. 49) first on a list of reasons to teach K-12 engineering. However, current empirical research on the efficacy of

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K-12 science, mathematics, and engineering integration is limited. This study adds to this growing field, using discourse analysis techniques to examine whether and why students integrate mathematics and science concepts into their engineering design work.

Literature Review

What Do We Mean by Integration?

An integrated engineering curriculum emphasizes the relationship between engineering, mathematics, and science, with a goal of reducing the barriers between traditional subject matter. In traditional K-12 science and mathematics classrooms, subject matter is often taught in an isolated way; in a mathematics classroom, the focus is on mathematics content, and in a science classroom, the focus is on science content. Interdisciplinary curricula include problems and activities that cross subject lines and more closely resemble science, mathematics, and engineering problems and activities outside of school. For example, Narode (2011) describes an integrated lesson in which students designed a container to hold a liter of milk. Students used mathematics concepts during the activity to find the volume of containers. They also used engineering design concepts, such as designing a container from which it is easy to drink milk. Other integration efforts take place at the level of a unit or course. For example, Linsenmeier, Harris, and Olds (2002) developed a unit in which students were challenged to determine "how much food is needed by an astronaut per day for a two week space mission in order to satisfy metabolic demands and not gain or lose weight" (p. 213).

The evaluation criteria described in the literature on integrative engineering curricula can further define and illustrate what is meant by mathematics, science, and engineering integration. Engineering curricula can be evaluated for the level of integration based on the inclusion of mathematics and science concepts and processes and on the connections formed between subjects (Brophy, Klein, Portsmore, & Rogers, 2008; Welty, Katehi, Pearson, & Feder, 2008). This is typically demonstrated by aligning the curricula with existing mathematics and science standards documents. For example, when describing the mathematics and science content of Vanderbilt Instruction in Biomedical Engineering for Secondary Science, also known as VIBES, Brophy et al. (2008) describe how well the program aligns with science and mathematics standards:

> VIBES has been recognized by the National Science Teachers Association (NSTA, 2008) as an exemplary program in meeting the National Science Education Standards (National Research Council, 2009). In addition to alignment with the NSES, each unit has been matched to the national math standards, AAAS Project 2061 standards (American Association for the Advancement of Science, 1993), ABET standards (ABET, August 1, 2007), and local and state level standards. (p. 280)

As seen in this quote, the authors evaluated the VIBES project based on whether it targeted learning goals across domains—identifying standards from engineering (ABET), mathematics, and science documents.

Modal engagement analysis (MEA) is an example of another method of analyzing the quantity and quality of engineering, science, and mathematics integration. Walkington, Nathan, Wolfgram, Alibali, and Srisurichan (2014) developed this methodology for analyzing cohesion across modal engagements and embodied cognition. MEA is used to analyze the cohesion of mathematics, science, and engineering concepts across multiple occurrences. For example, the researchers analyzed a video of a lecture from a high school engineering class on tension and compression during a bridge design unit. They analyzed the video and found instances when the teacher explicitly "reflected upon and planned for" (p. 9) concepts or events to recur across time or materials. For instance, in an example of a modal engagement (ME), "…the teacher makes a backward projection to the computer simulation software that was previously on the screen, encouraging students to think about their own bridges in terms of principles of statics" (p. 12). These, along with other instances of ME, were then mapped, "to illustrate how invariant relations become threaded through MEs that are connected by a web of projection, coordination, and ecological shifts" (p. 11) and can help researchers identify where and how concepts are used and built over time.

MEA puts the focus on the teacher and students making connections between concepts using various representations of the content, such as physical cues and referencing invariant concepts. MEA includes the analysis of dialogue, gestures, and representations in the identification and characterization of connections between subjects. This broadens the lens researchers are using when trying to identify and support successful integration in the classroom from a focus on the curricular materials to examining classroom enactments of those materials.

Nathan, Phelps, and Atwood and Prevost and colleagues (Nathan, Phelps, & Atwood, 2011; Prevost, Nathan, Stein, Tran, & Phelps, 2009) offer an additional analytical technique for identifying and evaluating the integration of mathematics, science, and engineering. In this case, the authors emphasize that the connections—verbal, physical, or written—can be *explicit* or *implicit*. Explicit connections are described as those in which the instruction specifically marks the multiple disciplines in use, and implicit connections are those in which content from multiple disciplines is used without being made explicit during the instruction.

Looking across all of this work, we see that integration is loosely defined as connecting across the concepts found in different disciplines. This content is typically identified in accordance with the standards addressed in the different disciplines. In addition, we see that these connections are made implicit or explicit to students by teachers and curricula, and these connections can be made by individuals and curricular materials through verbal or physical markers.

Why Is Integration Important?

Interdisciplinary K-12 curricula that merge traditional subjects have many potential benefits for students, such as increased student motivation, a more realistic contextualization of problems, increased transfer across problems, more cooperation, and better understanding of the content under study (Mathison & Freeman, 1997). In addition, there are specific potential benefits of interdisciplinary mathematics, science, and engineering curricula, or curricula that combine across the fields of mathematics, science, and engineering. In particular, projects that integrate the STEM disciplines align more closely with real-world problems; in most work environments, the lines between science, mathematics, and engineering are not as clearly defined as in K-12 classrooms. A naturally following conclusion is that students' real-world experiences, or personal experiences, will not fit easily into categories defined by traditional school subjects. This is consistent with Mathison and Freeman's (1997) conclusion that integrated courses allow students to more easily relate personal experiences to classroom experiences.

Moreover, research suggests that integrated curricula can support students in preparing for subject-specific standardized tests (e.g., Bottoms & Uhn, 2007; Foutz, Navarro, Hill, & Thompson, 2011; Rethwisch, Starobin, Laanan, & Schenk, 2012). For example, Foutz et al. (2011) researched a district-wide implementation of a project-based curriculum in 6th–8th grade that intertwined science, mathematics, and agricultural engineering. They found that the integrated curriculum was one piece of a successful district-wide initiative to improve standardized test scores. An additional potential benefit is that integrated engineering design lessons can engage students with learning disabilities who may not be as comfortable with traditional classroom instruction and traditional classroom environments (Schnittka, 2012). Integrated engineering classes can also have a positive impact on students' learning attitudes towards STEM subjects (Redmond et al., 2011; Tseng, Chi-Chang, Lou, & Chen, 2011).

Turning to research on post-secondary engineering, we see that an integrated approach is similarly gaining favor (e.g., Froyd & Ohland, 2005; Kellar et al., 2000; Tseng et al., 2011). For example, Froyd and Ohland (2005) suggest that the high dropout rate of engineering students might be partially caused by the rigor of science and mathematics courses necessary to graduate and the inability of some students to apply mathematics and science concepts to their engineering work. Froyd and Ohland compared the published results of integrated engineering programs at a group of universities referred to as the Foundation Coalition schools which offered integrated engineering courses: "Overall, Foundation Coalition schools have seen 10–25 percent increases in the retention rates of first-year engineering students and, in many cases, even greater improvements in the retention of women and underrepresented minorities" (p. 151). They also found that, in general, students enrolled in the integrated engineering programs had higher GPAs, and the integrated engineering students had higher pass rates than students in traditional engineering programs.

The positive effects of engineering courses on K-12 student achievement in mathematics and science are not found in all studies examining this topic (e.g., Kemple & Snipes, 2000; Welty et al., 2008; Wheeler, 2009). Tran and Nathan (2010a) compared the test scores of 140 high school students and found a decrease in the mathematics scores of students enrolled in integrated engineering courses when compared to students enrolled in traditional mathematics and science courses. In an additional study, the same researchers (Tran & Nathan, 2010b) compared mathematics and science standardized test scores of students enrolled in Project Lead the Way (PLTW) with the standardized test scores of students enrolled in traditional courses. They concluded that the students' enrollment in PLTW was not significantly correlated to the students' performance on the standardized tests. Instead, other factors, such as the students' prior achievement on the tests, free/reduced lunch status, and other student characteristics, had the most significant relationship to the students' test scores. We explore possible reasons for these mixed results in the following section.

Why Is Integration Hard?

There are many possible explanations for these mixed results. The first set of explanations surrounds teacher preparation for and comfort with teaching integrated content. Teachers may have a lack of confidence in their ability to teach engineering and to use the new pedagogy required of integrated and project-based curricula (Stohlmann, Moore, & Roehrig, 2012). Teachers may also bring some doubt to the classroom about the value of project-based engineering curricula and the value of having students integrate mathematics, science, and engineering concepts (Wang, Moore, Roehrig, & Park, 2011). Professional development programs for K-12 engineering are being developed across the country (Stohlmann et al., 2012), but since engineering is not a traditional K-12 subject, "best practices" are more elusive. Thus, it is possible that mixed study results emerge from differences in teacher preparation.

In addition, Nathan, Phelps, and Atwood and Prevost and colleagues' (Nathan, Phelps, & Atwood, 2011; Prevost et al., 2009) distinction between *explicit* and *implicit* connections in engineering curricula offer an additional insight into the challenges with supporting student learning in integrated contexts. These authors argue that when teachers and curricula make the cross-disciplinary connections explicit, students develop better understandings of the focus content and the relationships between the disciplines. Therefore, they believe a higher percentage of explicit instruction increases students' likelihood to transfer knowledge to other situations. A low number of explicit connections in curricular materials can make it difficult for K-12 engineering teachers to identify instances in which mathematics and science should or could be integrated into the engineering design work.

Finally, when moving from teacher and curricular support of integrated learning environments to the student participation in those environments, we see additional challenges emerge. In particular, Berland and Busch (2012) found that while mathematics, science, and engineering share many characteristics, there are also processes and problem-solving techniques unique to each subject. An oversimplification of the differences is that engineering focuses on how to solve a problem, while science and mathematics focus on why a problem-solving technique works. The goals of completing an engineering project may not align with the goal of understanding the mathematics and science concepts surrounding the project. That is, students may not find it necessary to think deeply about underlying mathematics and science principles in order to complete the engineering activity, and the goal of solving the engineering problem may distract from the goal of understanding those mathematics and science principles. This work is consistent with studies such as those of Barnett (2005) and Hmelo, Holton, and Kolodner (2000) demonstrating that students emphasized the aesthetics and surface features of their designs over the functionality. These authors argued that the qualitative aspects of the design were tractable, familiar, and provided a sense of forward progress. In other words, students were able to feel successful without focusing on the science underlying their designs.

Across this literature we see that, while integrated learning environments can successfully support students in developing rich understandings of STEM content, it is challenging to do so.

Research Questions

K-12 engineering education is increasingly being taught in the United States. A benefit of engineering education, but by no means the only benefit, is that it is a platform for mathematics, science, and engineering integration. Mathematics and science and engineering integration occurs in engineering classes when mathematics and science concepts and processes are purposefully applied to engineering concepts and processes. K-12 engineering curricula have been evaluated for the quantity and quality of connections made between mathematics, science, and engineering. Research has revealed mixed results with respect to what students learn when they engage in integrated engineering courses. These studies include large-scale studies of pre-/post-learning gains (Froyd & Ohland, 2005; Tran & Nathan, 2010a, 2010b; Tseng et al., 2011) and close analyses of curricula and teacher and student moves (Berland & Busch, 2012; Nathan, Phelps, & Atwood, 2011; Prevost et al., 2009; Walkington et al., 2014). Few of these studies examine the students' work—whether, how, and why they are integrating mathematics and science concepts into their engineering design work. current paper addresses this gap, using discourse analysis to understand whether and how mathematics and science concepts emerge in students' discussions about their engineering projects. Through this, we gain insight into the conditions that support students in learning and applying mathematics and science concepts in their engineering work. In particular, this study explores the following two research questions:

1. Are students integrating mathematics and science concepts in their engineering work?
2. What factors influence whether and how students integrate science and mathematics into their engineering design work?

This research project addresses these questions by examining the mathematics, science, and engineering integration—or lack thereof—that occurs in student dialogue found in a high school engineering course. This research will further strengthen the definition and characteristics of successful mathematics and science and engineering integration and guide further curriculum development and teacher professional development to support that integration.

Data and Methodology

The data presented in this paper were collected in the context of UTeach*Engineering* (UTeach*Engineering*, 2014). UTE was founded in 2008 with the goal of developing pre- and in-service teacher certification programs for K-12 engineering teachers. In addition, the UTE program developed a high school engineering course—Engineer Your World. The teacher with whom we worked for this class was a graduate of the UTE certification program and was enacting the UTE high school curriculum, Engineer Your World.

The high school engineering class that was the focus of this study included 31 high school juniors and seniors, 30 males and 1 female. The students had all taken or were concurrently enrolled in physics and pre-calculus. The teacher taught physics and robotics in addition to the two engineering classes. This was his second year teaching engineering. The class met every other day for approximately ninety minutes. The video data used in this analysis captured the second unit of the project created curriculum, *Evolution of Imagery*, which entailed 15 class periods. The main project of the unit *Evolution of Imagery* was to design a pinhole camera. The students did so by working through a version of the engineering design process (EDP), shown in Figure 1.

The first four lessons of the unit took a total of two class periods and focused on generalized engineering practices. The pinhole camera challenge that is the focus of the research started with lesson 5. Lessons 5–11 each aligned with a specific step of the EDP, and lesson 12 was a reflection on the entire process. Table 1 summarizes the main activities found in lessons 5–12 and names the EDP step covered by each lesson.

The structure of each class period throughout this unit was generally the same: class began with the teacher giving an introductory mini-lecture preparing students for their activity for the day and describing the next step of the EDP in terms of general engineering projects and the pinhole camera project. This mini-lecture was often accompanied by a Power Point presentation. After this grounding discussion, the student pairs would figure out how the new information or process might apply to their camera designs and work on an activity or activities aligned with the next EDP step. Take, for example, lesson 7, which focused on the Generate Concepts step of the EDP, a subset of the Generate step. At the beginning of this lesson, the teacher emphasized the importance of tailoring the camera to the customer's needs, which the students had collected and organized in previous lessons. Then, the teacher introduced students to the idea of a 2-3-5 poster where students, in groups of 2, would sketch 3 design concepts, and then have 5 minutes to edit and comment on another group's sketches. After handing out poster paper, each pair of students sketched 3 pinhole camera designs, switched posters and made comments. The students then used the feedback to refine their original designs. Most of the lesson consisted of the students generating their own concepts and commenting on those of their classmates.

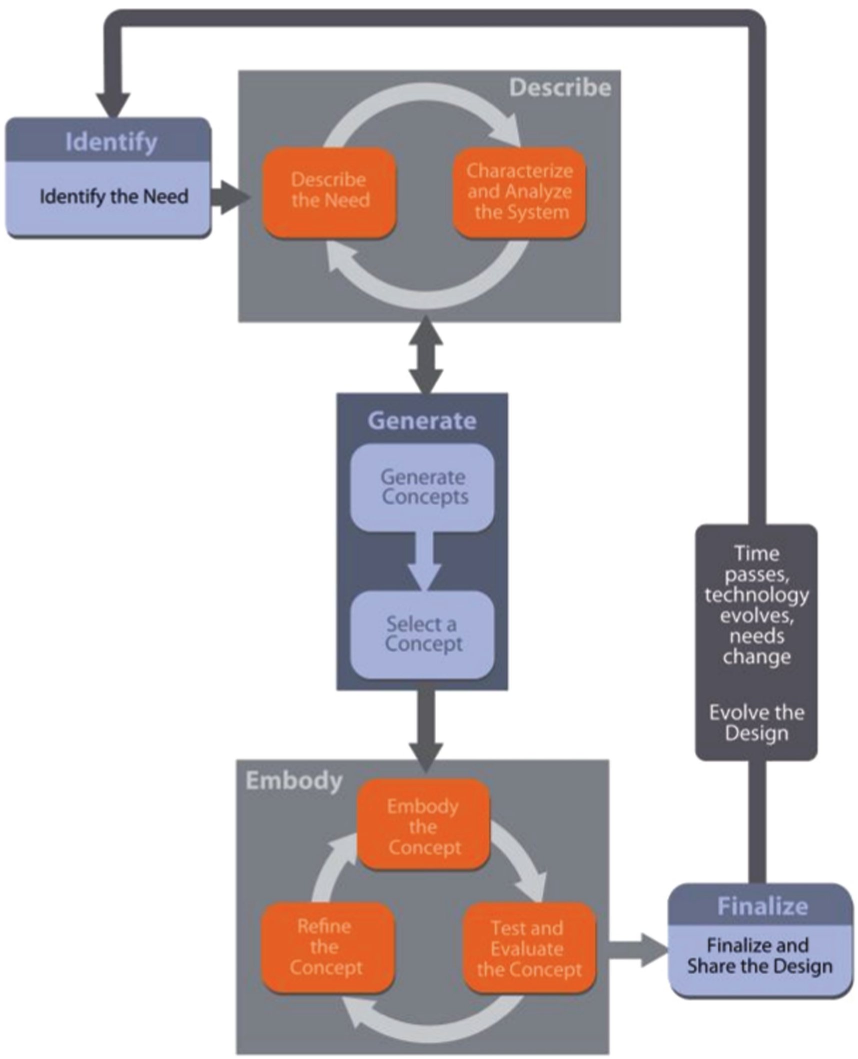

Figure 1. Engineering design process used in Engineer Your World. (UTeach*Engineering*, 2014)

Table 1
The unit.

Lesson number	EDP step (time expectations)	Brief overview
5	Describe the need (100 min)	The class discusses customer needs. In small groups, the students create an activity diagram for a pinhole camera and write customer questions. The students ask a "customer", or student from outside the engineering class, the questions and use the answers to write quantitative and qualitative camera requirements.
6	Characterize the need (100 min)	Each group creates a black box diagram of a pinhole camera and a geometrical model. Each group makes a specification sheet for their camera based on customer needs and related metrics.
7	Generate concepts (50 min)	The class discusses how to generate concepts based on customer needs. Each student quickly generates design ideas. Then, the students comment on their classmates' concepts. Finally, the small groups consider the constructive criticism of their peers and work towards a single design concept.
8	Select a concept (100 min)	The class discusses the importance of selecting one concept from many design concepts. Each pair then selects a design concept based on agreed upon selection criteria.
9	Embody the concept (100–150 min)	Each group creates a pinhole out of an aluminum can and measures the diameter of the pinhole using a scanner. The groups embody their design concept.
10	Test and evaluate the concept; refine the concept (150–200 min)	The students calculate the ideal exposure time for their camera. The students test their pinhole camera by taking and developing a picture. They also refine the cameras based on the test results.
11	Finalize and share the design (100–150 min)	The students prepare final documents for their camera, including manufacturing and packing instructions and a product name. The groups present their final pinhole camera.
12	Reflect on the design process (50 min)	The class discusses the steps of the engineering design process in relation to the pinhole camera project and in general terms.

The first author collected video data on two cameras during each class period. These recordings are the primary data source for this study. She recorded the entire class during all whole-class discussions including the teacher's Power Point presentations and lectures. In addition, each camera focused on a single student pair throughout their work on the project. As such, we recorded the work of two pairs of students (for a total of 4 focus students) throughout their efforts on the pinhole camera challenge. The focus pairs were selected based on logistics, consent status, and teacher recommendation. The cameras were left unstaffed as often as possible in an attempt to put the students at ease.

Analytical Methods

For this analysis, we were interested in whether and how students integrate mathematics and science into their engineering work. Thus, we examined the small group discussions, rather than whole-class discussions and lectures. This focused the data on student, not teacher, integration. Our first step was to identify all of the video in which the students were engaged in small group work on their engineering projects. Once that video was gathered, we engaged in four basic analytical steps:

1. Identification and transcription of potential integration episodes.
2. Differentiation between episodes that demonstrated successful and unsuccessful integration of mathematics and science within the engineering context of the class project.
3. Description of the mathematics and science content being discussed in each episode.
4. Differentiation between explicit and implicit integration support for each integration episode.

The first author completed step 1 to reduce the data set. Both authors then proceeded through steps 2–4 independently. The authors shared their results, discussed discrepancies, and reached a consensus on all analyses. Each of these analytical steps is described in detail in the subsequent sections.

Analytical Step 1: Identification of Potential Integration Episodes

Based on the literature, we understand STEM integration to be the connection of science and mathematics concepts with engineering and technology concepts and processes. Using this definition, the first step of our analysis was to identify those episodes in which integration could potentially occur—those episodes in which mathematics and/or science concepts were apparent. We focused on identifying those instances in which mathematics and/or science was apparent because all of the students' work was aimed at completing their engineering project, thus engineering was always present. Thus, we identified the "possible integration episodes" or the segments of student dialogue in which the students made reference to mathematics or science concepts while working on their engineering design project.

Consistent with other work exploring STEM integration, we define mathematics concepts to mean the content found in mathematics standards, such as solving equations and converting units between measurements systems (National Governors Association Center for Best Practices & Council of Chief State School Officers [NGACBP & CCSSO], 2010). Mathematical practices, for example "use[ing] appropriate tools strategically" and "attend[ing] to precision", were not taken into consideration due to the overlap that exists between engineering practices and mathematical practices. Science concepts similarly refer to concepts found in science standards, such as the properties of light waves, and not scientific practices or processes, such as "constructing explanations and designing solutions" (NGSS Lead States, 2013). Mirroring the reason that mathematics practices were not included in the data for analysis, scientific practices were not considered due to their similarity to many engineering practices. When students use science, mathematics, and engineering practices, they are using practices that apply to more than one subject matter, and, in a sense, integrating practices.

Using this definition, the first author watched the 15 video recorded class periods and identified 11 potential integration episodes (shown in Table 2). Each episode begins when a student first mentions a mathematics or science concept, includes the following dialogue related to the mathematics or science, and ends when the students change the focus of the discussion to a different topic. Each episode was named based on the main topic of the dialogue. The nature of the episodes and the operational definition of mathematics and science concepts allowed each episode to be labeled as being either a mathematics or science discussion. To give a sense of the scale of the episodes included in this paper, the length of time of each discussion, to the nearest minute, is given in Table 2.

As seen in Table 2, there are eleven potential integration episodes and the length of each episode varies from one minute to eight minutes. The average length of an episode is about three minutes.

When identifying the potential integration episodes, we found some discussions of mathematics and science concepts to be too simple to examine as potential integration episodes. In these discussions, such as the one in Table 3, the students used mathematics vocabulary (i.e., identifying shapes or mathematical operations) or science vocabulary (i.e., using terms such as kinematics) without discussing any underlying mathematics or science concept. We view this use of the vocabulary as an application of everyday knowledge rather than application of target domain concepts.

As seen in Table 3, Dustin uses the mathematical terms "rectangular base" and "square," but these terms seem to be part of his everyday vocabulary. Thus, this use of geometry vocabulary was not considered sufficient for the clip to be coded as an episode of students discussing mathematics concepts. Instead, this was considered an example of students using everyday knowledge.

Each of the 11 potential integrated episodes was transcribed for further analysis, as described in the following sections.

Analytical Step 2: Differentiating Between Successful or Unsuccessful Integration

The potential integration episodes were then coded as being examples of successful or unsuccessful integration of engineering with mathematics or science. In this case, successful use of the disciplinary concepts means that the student(s) both (1) discuss mathematics or science concepts and (2) connect those concepts to their engineering work. This coding does not refer to the correctness of the students' description or application of the concepts. Instead, this coding deals with the students' ability to relate the disciplinary ideas to the larger context of the engineering design project, so, in this case, successful integration means students were able to see how the mathematics and science concepts they discussed related to the design of their pinhole cameras. The transcripts that follow in Tables 4 and 5 exemplify what was considered successful and unsuccessful integration of mathematics and engineering, respectively. Table 6 exemplifies successful integration of traditional science content and engineering.

The transcript in Table 4 was coded as successful mathematics and engineering integration. In this episode, Tina and Adam are working on an assignment from lesson 10 which aligns with the Test and Evaluate sub-step of the Embody EDP step. The goal of the assignment is to have the students find the necessary measurements for their camera to take the best possible picture of an object. The assignment focuses on the relationship between the aperture size of a pinhole, height and width of the film, height and width of the image, and height and width of the

Table 2
Episodes.

Episode number	Date (dd/mm)	Episode name	Length of episode	Science or mathematics
1	09/21	*How does a pinhole camera "turn on"?*	1 min	Science
2	09/21	*How does a pinhole camera take a picture?*	1 min	Science
3	09/23	*How do we make an optics model?*	4 min	Science
4	09/29	*Will the film fit?*	1 min	Mathematics
5	09/29	*Is it a cube?*	1 min	Mathematics
6	09/29	*What are the measurements of the box?*	4 min	Mathematics
7	09/29	*Will the film fit in the box?*	3 min	Mathematics
8	10/07	*What is our camera's f-number?*	4 min	Mathematics
9	10/14	*What is the best distance from the object?*	8 min	Mathematics
10	10/14	*How do I use this spreadsheet?*	5 min	Mathematics
11	10/14	*What is the optimal exposure time?*	2 min	Mathematics

Table 3
Use of mathematics vocabulary not coded as a potential integration episode.

1	Jacob	Okay. So, uh, are we going to have, like, some sort of tripod that we can hold it on there?
2	Dustin	Um, that would probably be ideal, because if we don't, then it's going to be rolling around all the time inside of it.
3	Jacob	Right.
4	Dustin	So, we need to get something to keep it steady.
5	Jacob	Okay.
6	Dustin	If it was a *square*, it wouldn't matter, or if the box were.
7	Jacob	[writing]
8	Dustin	*Rectangular base*. [looking at the can and thinking as Jacob writes] It would probably be nice to have some way to add a grip on here.

pre-image. The relationship between these variables is depicted in Figure 2, which comes from the curriculum and was shown to the students in class.

In Table 4, Adam and Tina apply mathematics concepts to quantify the relationship of the aforementioned variables for specific dimensions, and they also generalize the relationships. During the episode they used mathematics concepts, including identifying independent variables and dependent variables and solving for a variable in a proportional relationship. These concepts align to the following Common Core State Standards for Mathematics (CCSSM): 6.EE.9, 7.RP.3, A-CED.4, and A-REI.3 (NGACBP & CCSSO). In the transcript, they also relate the mathematics to their pinhole camera design, specifically to how to take a photogram of a specific object with the camera.

The two components of successful mathematics and engineering integration are present in this episode. The first component is that Tina and Adam verbalized several mathematical concepts, some of which are seen in the dialogue in Table 4. For example, as seen in lines 1–7, Tina and Adam discuss the constants and variables that they will use to find the size of the object that is shown on the film paper when taking a picture from several different distances from the object. Starting on line 11, they calculate values for specific distances from the camera to the object. The second component is that they related this mathematical reasoning to their pinhole camera design. In this assignment the design step being covered was Test and Evaluate, which is done by taking and developing a picture. The students are talking about their calculations in relationship to their camera this entire episode. This begins on line 1 when Tina frames the episode as being about how far the pinhole should be from the objected being photographed—a plaque with an image of a gun on it. We see this theme throughout the transcript. For example, on line 46 Adam introduces the complexity of the distance between the pinhole and film as affecting their calculations. Thus, this is an example of *successful* mathematics and engineering integration because of the connection that Tina and Adam made between the mathematics concepts and the engineering design project.

Table 4
Successful mathematics and engineering integration.

Episode 9: What is the best distance from the object?		
1	Tina	OK. Distance from pinhole. If it's a meter or a foot, it would have to be further.
2	Adam	Wait. So, wait. This is going to be our X, right? And this is going to be our answer, right?
3	Tina	This is the distance from the pinhole.
4	Adam	Like, these, these are going to be consistent at least.
5	Tina	Yeah, this is X, yeah.
6	Adam	So, this is the one we're going to change to match.
7	Tina	Yeah
8	Adam	All right. It's gonna have to be smaller. What the heck? Did it change?
9	Tina	I don't know. We just have to move away. That's—that's, um, that's half a foot right there. That's…
10	Adam	Yeah, with our camera.
11	Tina	Ok. One is fine. Half a foot. And then the width has to be 70%. We're going to need a calculator.
[Students calculate the dimensions for several distances]		
46	Adam	Yeah. Yeah, I think our film's not too far back. I thought it was kinda gonna be with 7 inches.
47	Tina	You thought we were gonna have to be ten feet away. [chuckles]
48	Adam	Well, I think with what we're gonna do, I think we are, because we're already at five feet.
49	Tina	Right.
50	Adam	And the object's only two feet big.
51	Tina	So, well, what do you want…? We're doing the [plaque of a] gun, right? That's like four feet.
52	Adam	Yeah, if we do… [inaudible]. It's like….
53	Tina	I don't know how we'd do that without it being disabled[?].
54	Adam	We'd just lay it up against the wall.
55	Tina	It's at five already? Yeah.

Table 5
Unsuccessful mathematics and engineering integration.

Episode 8: What is our camera's f-number?		
1	Jacob	So now, 140 divided by.31 equals… [on calculator] …451.
2	Dustin	140 over—over 6.1… [inaudible] … [writing] …which equals 451.61. OK. That was simple. Hooray. We're done.
3	[Note]	[The boys wait.]
4	[Note]	[Teacher comes to talk to the boys at the next table.]
5	Jacob	I wonder how this will help us.
6	Dustin	What?
7	Jacob	I wonder how this will help us.
8	Dustin	I have no idea.

The transcript in Table 5 is an example of unsuccessful integration of mathematics and engineering. The students in this episode are Dustin and Jacob, and they are also working on an assignment from lesson 10—and similarly performing calculations that will influence their camera design and test plan for the Test and Evaluate step of the EDP. However, in this case, the students do not see the relationship between these calculations and their designs. During this episode, the students are finding the *f*-number for their camera—a ratio of the focal length of the camera to the diameter of the aperture which is used to determine how long the shutter should remain open when they take their picture. The assignment provides students with a basic formula for calculating this value. In this episode, the students converted the diameter of their pinhole (in dots per inch) and the focal length (in centimeters) to the correct units to be able to substitute the measurements into the *f*-number formula, and they applied the *f*-number formula to find the *f*-number for their camera. Unit conversion and calculations are concepts aligned to the following CCSSM: N-Q.1, A-REI.1, and A-REI.3 (NGACBP & CCSSO, 2010). However, these students struggle with the second criterion for successful integration; they struggle with identifying the connection between the *f*-number and their pinhole camera design project.

During the episode, these students fulfilled the first component of successfully integrating mathematics or science content—they are working with the mathematics content. However, they are unclear about how the *f*-number relates to their camera, as seen on lines 7 and 8. Thus, Dustin and Jacob were able to use the mathematics concepts necessary to convert units and solve a formula but unable to integrate the mathematics concepts and the engineering design project. For this reason, this episode was coded as an instance of *unsuccessful* mathematics and engineering integration.

Moving to the episodes in which science concepts are potentially integrated with the engineering design work reveals that there were three episodes focused on potential science integration. In two of the three cases, the students successfully integrated the science with their engineering designs; they were able to relate the science concept and an engineering assignment that was part of the pinhole camera project. The transcript in Table 6 includes dialogue from one of the episodes that was coded for successful integration. The episode is from lesson 5, which aligns to the Describe the Need step of the EDP. The conversation in Table 6 occurred when the students were developing a list of steps necessary to produce a picture with a pinhole camera. The students discussed the general properties of light in terms of describing how a camera obscura works while doing this.

In the transcript, Jacob describes to Dustin what happened inside the camera obscura, or "giant pinhole camera" (line 4), that the teacher used during the previous lesson, since Dustin was not present. The camera obscura is a precursor of the modern-day camera. The images produced by the camera obscura are a common phenomenon used to help children visualize how light travels

Table 6
Successful science and engineering integration.

Episode 2: How does a pinhole camera take a picture?		
1	Jacob	Okay, so we have camera set up. We have to cover the hole. We already put the film in and what we should do next would be to uncover the hole so that the light can….
2	Dustin	So it can take a picture.
3	Jacob	Yeah, so the light can come in.
4	Dustin	What were the other things that were part of the giant pinhole camera? Do you know? I didn't get to go inside, so…
5	Jacob	Not… I mean, you just went in and you had the white piece of paper and you would just slower open or close the hole so the picture would — I mean, the back would come up clear. And, I mean, it was really basic. It wasn't a whole lot to it.
6	Dustin	So, he just like changed the cover to where it's like smaller and smaller?
7	Jacob	Yeah, smaller, but he started off big and then he—to show us what the difference is, he put a smaller hole to shine the light and it became clear.
8	Dustin	Gotcha. But we're going to already have the right size hole, I guess.

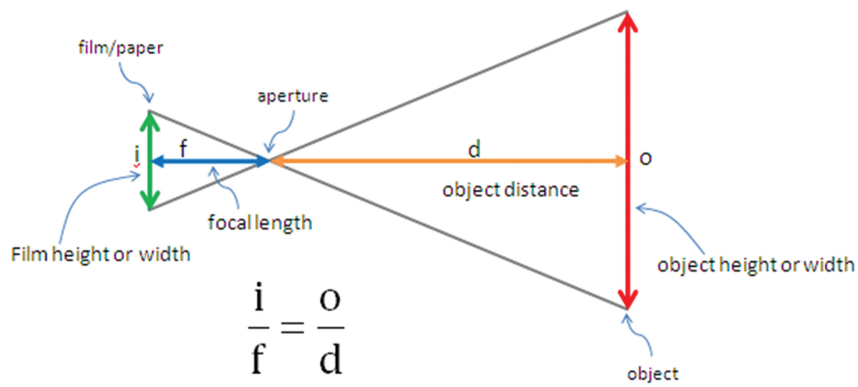

Figure 2. Diagram depicting the relationship between object distance, size, focal length and film size.

which aligns with the Next Generation Science Standard MS.PS4.b (NGSS Lead States, 2013). The students related these ideas to their pinhole camera as seen in lines 1 and 8. In particular, notice that Jacob describes the image in the camera obscura becoming clearer as the pinhole got smaller (lines 5 and 7) and that Dustin relates this to their camera design and the need to establish the correct size of their pinhole in line 8. We therefore coded this episode as being an instance of successful integration of science and engineering, because it includes the two required components: discussion of a science concept and the connection between the science concept and the engineering project.

Analytical Step 3: Describing the Mathematics and Science Content Being Addressed

The importance of step 3 in our analysis—describing the mathematics and science content being addressed—emerged out of the data itself because many of the integrated episodes that emphasize mathematics content felt rather simplistic. This simplicity motivated us to characterize the type of content students were integrating with their engineering projects.

In this analysis, we found that four of the episodes focused on estimating the size of various camera components, basic geometry, measuring, and converting units, concepts addressed in the following CCSSM: 5.MD.1, 7.RP.1, 7.G.4, 7.G.6, N-Q.1, N-Q.2, and N-Q.3 (NGACBP & CCSSO, 2010). For example, in Episode 4: *Will the film fit?* Dustin and Jacob determined whether the rectangular film would fit in their cylindrical camera by measuring the diameter of their camera and the dimensions of the film. They used these measurements to determine if changes needed to be made to their design to best accommodate the film. In Episode 6: *What are the measurements of the box?* the students similarly estimated the measurements of their camera in centimeters and inches and used a ruler to check their estimates.

Students discussed and solved equations in four of the other mathematics episodes. The concepts the students used in these episodes aligned with CCSSM 6.EE.9, 7.RP.3, N-Q.1, A-CED.4, A-REI.1, and A-REI.3 (NGACBP & CCSSO, 2010). One of these episodes was Episode 11: *What is the optimal exposure time?* In this episode, the students used the focal length and the pinhole size for their camera to find the exposure time for their camera depending on the weather. In Episodes 9 and 10, the students used a spreadsheet pre-programmed to set up variables in a proportion. The students were asked to insert the dimensions of their camera and film paper to identify and apply the relationship between the variables and to determine how far from an object to place their camera to take a good picture of the object.

All episodes that involved science were of the students considering concepts associated with the properties of light, covered by the Next Generation Science Standard MS.PS4.b (NGSS Lead States, 2013). In Episode 1: *How does a pinhole camera "turn on"?* the students discussed how light travels. In Episode 3: *How do we make an optics model?* the students talked through the drawing of an optics model. Their models were ray diagrams that included the film paper, aperture, pre-image, and image. They discussed the inversion of the image on the film paper shown in the model with linear rays from the pre-image through the aperture to the film paper.

Analytical Step 4: Differentiating Between Explicit or Implicit Support

Given existing literature that suggests explicit support is an important strategy for supporting student integration of mathematics, science, and engineering (Nathan, Phelps, & Atwood, 2011; Prevost et al., 2009), we wanted to explore how instances of students' integration of mathematics and science with engineering were contextualized. Did the teacher always make the relationship between the subjects clear before successful integration? To this end, we coded each potential integration episode to determine whether the mathematics or science content under discussion had been explicitly supported. Consistent with current literature we defined explicit as "any instance wherein the instruction specifically points to a mathematics [or science] principle, law, or formula, and depicts how it is used to carry out or understand an engineering concept, task or skill" (Nathan, Phelps, & Atwood, 2011, p. 9) and implicit as "the conceptual basis for understanding how mathematics [or science] is used for engineering is ingrained into the tools, representations or procedures used in the lesson, but not specifically pointed out" (Nathan, Phelps, & Atwood, 2011, p. 9).

Thus, to determine whether the mathematics or science content that emerged in the potential integration episodes did so as a result of implicit or explicit supports, we examined the whole-class discussions that preceded each episode. In doing so we were working to determine whether the teacher had introduced students to the mathematics and science content they then discussed in their small groups. Table 7 includes dialogue from the teacher going through a Power Point presentation before asking the students to calculate the *f*-number for their cameras, which preceded Episode 8: *What is our camera's f-number?* In this class discussion (or mini-lecture) the teacher makes the connection between using a formula to find the *f*-number and the engineering design project, so Episode 8 was coded as following explicit instruction.

This introduction to the *f*-number included an explicit connection between calculating the *f*-number for each camera and the importance of the *f*-number in the use and design of the camera. In fact, notice line 1 in which the teacher says explicitly: "OK. OK, guys, if you're going to calculate your pinhole camera, it has to be for your camera. You can't calculate the exposure time for a generic camera." In addition, as seen in line 16, the teacher provided direct instruction on how to perform this calculation. Here we see the teacher giving them explicit information about a process but asking them to figure out how it might apply to their individual designs. Thus, Episode 8 was coded as one that was preceded by explicit instruction. Another example of an episode coded for explicit instruction is Episode 9: *What is the best distance from the object?* (see Table 4). When the teacher introduced the assignment he verbalized the connection between several mathematics concepts and using the pinhole camera to take a photograph.

Implicit connections occurred when students used science and mathematics concepts that the teacher did not explicitly support in either preceding lectures or when talking to the students in their small groups. The example in Table 8 is of an implicit connection. The students ask the teacher if the film will fit in the cameras. Then, the students measure their cylindrical camera and reason whether or not the film will fit, concepts that align with CCSSM 6.G.4 and 7.G.4.

This episode was coded as successful mathematics and engineering integration, because the students were using the measurements and a net of a three-dimensional figures, in this case a cylinder, in order to determine the size of the film that would fit inside their cylindrical camera. Thus, we see them applying and connecting the mathematics concepts to their engineering work. It is also coded as an "implicitly supported" episode because the problem context required this conversation—they needed to determine the film size in order to complete their design—but the teacher did not do so. Episode 1: *How does a pinhole camera work?* is another example of an implicit connection. The dialogue in Table 9 is the teacher introducing the assignment from Episode 1.

In Episode 1, the students discuss the properties of light when completing an assignment on the steps necessary to use a pinhole camera. The teacher had discussed the properties of light during a previous class period, but as seen by the dialogue in Table 9, the teacher did not tell the students to refer to that instruction when completing the new assignment, or in other words, the connection between the science concepts and the design assignment was not explicitly stated to the students.

Analysis

Combining across these analytical steps, we see that the majority of the episodes included evidence of the students connecting mathematics or science concepts with the engineering design project of designing a pinhole camera. Of the eleven potential integration episodes, eight were of students discussing mathematics concepts, and during six of those mathematics discussions, students applied the mathematics concepts to their engineering design project—what we called successful integration. Three of the episodes

Table 7
Example of explicit support preceding an episode of unsuccessful integration.

Whole-class discussion preceding Episode 8: *What is our camera's f–number?*		
1	Teacher	OK. OK, guys, if you're going to calculate your pinhole camera, it has to be for your camera. You can't calculate the exposure time for a generic camera. Yours is different than everybody else's. Nobody here made one identical to somebody else. Either the size of the box is different or your pinhole size is different. OK. There's a couple of things in your camera that changes your exposure time. Can anybody tell me what they are? It's two things.
[Teacher and students talk about exposure time]		
16	Teacher	Focal length is the distance from your pinhole to the film. OK. Next, we're going to talk about some relationship between those two things and how long you leave your pinhole uncovered. This is your exposure time. OK. Copy this down. Also, write these letters next to the two definitions you just did. OK. *f* is going to be focal length. So when you did focal length, and you wrote down the definition, write *f* next to it. This is your aperture size. It's the diameter of your pinhole or aperture size. Focal length. The big number is like the depth of your camera. This is the pinhole here. Aperture to pinhole. Guys, all of this on the left is one thing. That's just your *f* number. It's not *f* divided by numbers. No. It's just *f*-number. If you're into photography, you've seen like a slash on a camera. You see like F/1, F/1.4, F/2.

Table 8
Example of successful integration episode preceded by implicit support. 5

Episode 7: Will the film fit in the box?		
9	Student	[Teacher's name], how big is the film?
10	Teacher	I think it's four-by-five. Four inches by five inches.
11	Dustin	Okay, we should check that. See if it's something that's film that's four-by-five inches.
12	Jacob	[measuring the can] Five….
13	Dustin	It probably won't matter.
14	Jacob	Yeah. Wait. What are you talking about?
15	Dustin	The film.
16	Jacob	Oh.
17	Dustin	Like, unless it's going to go on this. I thought it would be like down there. So, we'd want to be like checking this, right?
18	Jacob	I think so. [measuring] Five. Five inches in diameter.
19	Dustin	Okay.
20	Jacob	And then maybe we can measure this to see how much picture we can get on back. You know what I'm saying? That's five and 9/16ths.

were of students discussing science concepts, and two of the science episodes had evidence of the students successfully integrating the science concept and the engineering design challenge. Thus, 8 of the 11 potential integration episodes analyzed reveal the students successfully integrating mathematics or science concepts into their engineering work. The remaining three episodes were instances of unsuccessful integration. Table 10 summarizes these results.

As seen in Table 10, the majority of the integrated episodes were examples of successful integration in that the students were able to apply the mathematics or science content to their design work. However, a handful were not. We use the comparison of successful and unsuccessful integration to begin considering factors that might influence that success. In particular, we focus on the type of mathematics or science content being discussed and the explicitness of the instruction. Table 11 summarizes this result.

As shown in Table 11, of the eleven episodes, five were of student dialogue that occurred after the teacher explicitly connected the science or mathematics concepts to the engineering design project. Six episodes were of student dialogue that was not preceded by explicit connections from the teacher. The successful integration column underscores that all six of the episodes coded as implicit were successfully applied to the engineering design challenge, while only two of the five explicit episodes were successfully applied to the engineering task. This suggests a potentially negative relationship between explicitly supporting the integration of mathematics and science concepts into engineering design work and students doing that integration.

Examples of an explicitly supported episode that was coded as unsuccessful integration are shown in Tables 5 and 7. The episode *What is our camera's f-number?* followed instruction in which the teacher made explicit connections between the engineering project and mathematics concepts. In the preceding discussion, the teacher explained how the *f*-number is found using a formula and how the *f*-number is used to determine the exposure time of the cameras. During the subsequent small group work, the students found their camera's *f*-number, but vocalized their inability to see the connection between the *f*-number and the pinhole camera project.

The content the students discussed in implicitly and explicitly supported episodes also shows a striking pattern in terms of successful and unsuccessful integration: in all four of the implicitly supported mathematics episodes, the focus of the mathematics talk was on measurement. Moreover all of these episodes demonstrated successful integration on the part of the students. None of the explicit mathematics episodes had a focus on measurement. In the explicitly supported mathematics episodes, the students mainly dealt with formulas: interpreting the various variables in a formula, solving formulas for a variable, and, ideally, interpreting the results in terms of a pinhole camera. These episodes were split such that two reveal successful integration and two reveal unsuccessful integration. This pattern suggests that the type of content addressed might also

Table 9
Example of implicit support preceding an episode of successful integration.

Whole-class discussion preceding Episode 1: *How does a pinhole camera work?*		
1	Teacher	I want you to write what you're going to do, not how you're going to do it. So, "Place film in camera." Okay? That's what you're going to do. You're not going to say that you got a tape in it. You're not going to say that you're going to carefully do it. You're not going to tell any of the 'how' you're going to do. You just want to know what has to be done. So, keep it really short. Usually one or two words is good. "Place film in camera." … So, kind of keep it short. Okay. So, get with your partner. I want it in both of your notebook stuff. Talk it over. And it should take about – try about five minutes.

Table 10
Summarizing steps 1 and 2 of analysis: What happened?

	Total	Science/mathematics
Successful integration	8	2 science 6 mathematics
Unsuccessful integration	3	1 science 2 mathematics

influence whether and how students integrate the mathematics and science content into their engineering work.

We explore both of these patterns in the discussion section.

Discussion

One of the most striking findings in this study is that in following two different pairs of students across 15 days of engineering work, we found only 11 brief episodes of mathematics or science content being integrated into the engineering design. Students spent more than half of this unit working in small groups, and the potential integration episodes accounted for only a total of about 35 minutes of student-to-student dialogue on mathematics and science concepts. This general lack of engagement with the mathematics and science content on the part of the students poses challenges to the goal of integrating mathematics and science with the engineering design work.

In addition, when examining those eleven episodes, we see that eight are examples of students successfully integrating the mathematics and science content into their engineering design work while, in three instances, the integration was unsuccessful. In these three episodes, students were unable to articulate the relationship between the mathematics and science content they were using and their designs. Examining the context in which these episodes occurred—in particular the content being discussed and the degree of teacher support—offers possible hints for what might support students' successful integration of mathematics and science content into their engineering work.

Examining Table 11 suggests that the teacher explicitly supported integrating mathematics and science content if the students did not have the expertise necessary to engage with the mathematics and science content without that explicit support. In other words, the teacher was explicitly supporting the *novel* mathematics and science concepts. This possibility is supported by examining the type of mathematics content students integrated into their design work: four of the five explicit episodes focused on the equations students needed to use. As exemplified in Table 6, this explicit support focused on defining the variables in the equation and explaining why the equation was necessary. It is clear that students would have been unable to engage with these equations without some sort of introduction, like this. In contrast, four of the six implicit episodes focused on more familiar content—such as how and what to measure. This more familiar content required less teacher support. Thus, the data suggest that the explicitly supported mathematics and science emphasized novel content that required some sort of introduction.

However, this does not explain why the novel content was not successfully integrated—why students struggled to see the relationship between the novel content and their design work after explicit supports, particularly when those supports articulated the relationship (i.e., see Table 7). That is, the analysis reveals that the explicit support was often paired with unsuccessful integration while these students successfully integrated the mathematics and science content into their engineering work when they had little explicit support from the teacher to do so. Here we consider two possible explanations for why successful integration co-occurred with implicit supports more than explicit supports: (1) the explicit supports covered novel content and the novelty resulted in challenges with integration or (2) the explicit support did not help students perceive the mathematics and science content as useful.

Episode 8 (Table 5) demonstrates the first possible explanation. In this particular case, the students were largely unfamiliar with the term *f*-number, so they required explicit teacher support to calculate it. However, even after the explicit supports, the students were still unable to connect it to their design work. This is seen in Jacob's statement: "I wonder how this will help us." It is possible that the lack of familiarity with *f*-numbers could explain their disconnected, rote, application of the mathematics concept. That is, one possible explanation for the negative association between explicit connections and students' successful integration might be that explicit connections occurred when the content was novel and the novelty posed challenges for students as they worked to integrate the mathematics, science, and engineering goals.

Table 11
Summarizing steps 3 and 4: What content follows implicit or explicit instruction?

	Support	Successful integration	Unsuccessful integration
Measurement	Explicit	0	0
	Implicit	4	0
Formulas	Explicit	2	2
	Implicit	0	0
Properties of light	Explicit	0	1
	Implicit	2	0

While this explanation appears to be consistent with the data, we argue that it does not fully account for the students' integration (or lack thereof) of mathematics, science, and engineering content. In particular, while the specific formulas were novel, these juniors and seniors were quite familiar with using algebraic equations to calculate variable values. Thus, the novelty of the particularities does not suggest the process was complicated or unfamiliar. As such, one might expect students to take the explicit instruction regarding this content and apply it directly to their camera designs. We see Adam and Tina doing this in Episode 9 (Table 4) in which they apply the proportional reasoning necessary to calculate the focal length of their camera—in this case the teacher explicitly introduced the figure and mathematical reasoning around it and these students successfully applied it to their individual camera designs. Thus, the question remains: why did the students not integrate the explicitly supported novel mathematics or science content with their engineering designs more often?

Edelson (2001) offers a possible explanation for this quandary. In particular, his "Learning-for-Use" theory argues that students will develop richer conceptual understandings that are accessible in new environments when the ideas being studied are useful and serve a purpose for the students. In other words, students are more likely to develop rich conceptual understandings of information that is *useful* to them. Applying this theory to the results of this study suggests that maybe the students were not transferring the new mathematics and science content from the mini-lectures to the new environment of their engineering design challenge because they did not see this as useful—they did not understand that doing so would help their design work. This interpretation is again supported by Jacob's statement: "I wonder how this will help us." In this case, we see him doing the mathematics but unable to explain why—it isn't useful to him. In addition, this possibility is consistent with research by Berland and Busch author and colleague (2012) in which the authors found that the goal of completing a design challenge may have distracted students from engaging deeply with the mathematics or science. Applying that conclusion to the current data suggests that these students may have found the mathematical equations to be a distraction from their focus on the engineering goal of completing their design. This suggests that the explicit discussions relating the mathematics/science content to the engineering design supported students in understanding *what* to do but not *why*—even when the teacher explicitly told them why particular concepts were related to their design work.

This suggests that if we want students applying complex mathematics or science in the context of engineering, we need to be careful about how to frame the science or mathematics instruction so the purpose, the connection to the project, remains apparent to students. However, as we have seen, explicitly being told the connections may not lead the students to understanding or developing those connections. Instead, consistent with the Learning-for-Use (Edelson, 2001) approach to instructional design, it might be that teachers need to motivate the unfamiliar mathematics and science—prior to introducing this complex and/or unfamiliar content, teachers might create situations that help students recognize the need for that content. For example, in the case of the *f*-number, teachers might allow students to take pictures without knowing the appropriate *f*-number and then have a discussion about why all of their photographs are washed out or black—students did not know how long to keep the aperture open. After experiencing this expectation failure (Schank, 1999), students might be more invested in learning the *f*-number equation and understanding how it would support their work on their cameras.

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