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The roles of engineering notebooks in shaping elementary engineering student discourse and practice

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ABSTRACT

Engineering design challenges offer important opportunities for students to learn science and engineering knowledge and practices. This study examines how students' engineering notebooks across four units of the curriculum *Engineering is Elementary* (EiE) support student work during design challenges. Through educational ethnography and discourse analysis, transcripts of student talk and action were created and coded around the uses of notebooks in the accomplishment of engineering tasks. Our coding process identified two broad categories of roles of the notebooks: they scaffold student activity and support epistemic practices of engineering. The study showed the importance of prompts to engage students in effective uses of writing, the roles the notebook assumes in the students' small groups, and the ways design challenges motivate children to write and communicate.

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Reforms in science education have included technology and applications of science to society in various ways (Aikenhead & Solomon, 1994; Rudolph, 2003). The inclusion of technology has also provided opportunities for student learning through engineering design (Benson, 2009; Cunningham & Carlsen, 2014; Pearson & Young, 2002; Penner, Giles, Lehrer, & Schauble, 1997). Over the past decade, engineering has steadily made its way into pre-college education as nations seek to address workforce needs (Forsthuber, Motiejunaite, & de Almeida Coutinho, 2011; NGSS Lead States, 2013). Curriculum reform and educational standards now include engineering for primary and secondary students. One way to engage students in science and engineering is to provide engineering design challenges that are open-ended, allowing students to generate multiple solutions to address the constraints of the situation (Cunningham & Kelly, 2017a). For such engagement to lead to productive learning, supports need to be in place to structure students' work. These supports often entail providing a means to engage in disciplinary discourse (Kelly, 2014a). This paper examines one such support, the use of engineering notebooks, to foster student engagement and learning of science and engineering practices and principles.

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The introduction of a greater use of design challenges in primary and secondary schools provides new opportunities for science and engineering learning. Educators have advocated for the integration of cognitive, epistemic, and social goals for science learning (Duschl, 2008; Kelly, 2008). Engaging students in science and engineering practices offers avenues to integrate learning of key disciplinary concepts and epistemic practices (Sandoval & Reiser, 2004). Engineering design challenges often entail students addressing a given problem, developing plans for execution and testing of a design, revising initial plans through re-design, and sharing ideas across student research teams (Cunningham & Carlsen, 2014). The materiality of designs (i.e. the building of physical prototypes and models), the consideration of the constraints of the assigned task, and the need for collaboration, offer educational contexts where science ideas can be put into use through spoken, written, and schematic discourse. These opportunities to engage in such discourse have been identified as supporting student learning of disciplinary knowledge (Kelly, 2014a). Building a repertoire of discourse practices serves to help students understand key ideas in science and engineering, and builds students' identities as science learners (Reveles, Cordova, & Kelly, 2004). In these ways, science and engineering learning can co-occur and be mutually supportive.

Engineering design challenges are often conducted in teams (Sheppard, Colby, Macatangay, & Sullivan, 2007). The creation, evaluation, and re-design of solutions require that such teams think creatively and share ideas, critiques, and prototypes through dialectic conversations (Brereton, Cannon, Mabogunje, & Leifer, 1996; Florman, 1987). Thus, much like science and other professional activity, discourse processes are central to accomplishing the collective work of the groups (Kelly, 2014a). These discourse processes often draw from and make use of signs and symbols, figures and diagrams, and various other written inscriptions, including textual descriptions of the work. Records of ideas, designs, data, prototypes, and other relevant inscriptions can potentially support the development of scientific and engineering knowledge among students.

For educational purposes students' dialectic conversations can be scaffolded by science and engineering notebooks. Providing classroom students with notebooks offers opportunities to organise their collective actions, make reference and use of data, and structure their activities. This study examines the roles of the notebook in the collective activity of engineering design challenges among primary school students. Professional engineers often use an engineering notebook to document and structure their work (McAlpine, Hicks, Huet, & Culley, 2006). In this study, and others supporting engineering design (Cunningham & Kelly, 2017a), an important goal of engineering education is to engage children in the practices of engineering.

Writing in science and engineering education

In the last two decades, engineering has made its way into pre-college curricula. Engineering and design activities can help students better understand how the human-made world they inhabit comes to exist and can develop children's problem-solving and design abilities. Engineers rely on science and mathematics as they develop solutions and curriculum designed to have students use science knowledge as they solve engineering problems increase students' understanding of science concepts (Oh, Lachapelle, Shams, Hertel, &

Cunningham, 2016). Engaging children in engineering challenges can also provide opportunities to use language in purposeful activity; students often design unique solutions that they want to share, describe, and communicate with their teachers and classmates.

The ability to communicate is a central practice contributing to the development of engineering solutions and the construction of knowledge within engineering communities (Brereton et al., 1996; Florman, 1987). Such communication requires more than understanding technical diagrams and mathematical equations, as engineers regularly need to negotiate within design teams and with respective clients (Trevelyan, 2010; Vinck, 2003). The ability to communicate through spoken and written discourse in engineering contexts has similarly been recognised in education (Jonassen, Strobel, & Lee, 2006). Therefore, written communication is central to the many processes of engaging in engineering design, from negotiating, planning, communicating, presenting, evaluating, and to re-working solutions. Ideas communicated through words, signs, symbols, pictures, or even in the form of (knowledge embedded in) devices require humans for circulation and interpretation (Johnson, 2009). This situates the semiotic work in a relevant epistemic community, be it professional or educational.

Engineering education for students in pre-college education is just emerging as a research field (Cunningham & Carlsen, 2014). To date, there have been few studies of classroom interaction, and none that have examined the ways that maintaining a written record through notebooking can support student learning. While science investigations and engineering design challenges have different purposes, the uses of writing for learning share some common features. Notebooks are often used to provide a space for students to maintain records, share thinking, build understanding, and reflect on their work (Fulton & Campbell, 2004; Klentschy, 2005). Uses of writing in science investigations have been shown to foreground the importance of discourse processes in the development of scientific literacy (Hand, Prain, Lawrence, & Yore, 1999; Kelly, 2014a; Rivard & Straw, 2000).

The use of written language is an important part of scientific literacy. Norris and Phillips (2003) identified two broad forms of scientific literacy – fundamental and derived. Fundamental scientific literacy refers to the necessary proficiency in reading and writing scientific texts that support the development of the derived sense of scientific literacy, referring to the ability to engage productively in socioscientific issues of relevance. Such literacy entails learning how to engage in epistemic practices to construct, communicate, evaluate, and legitimise knowledge claims (Kelly, 2011, 2016). Thus, communicating about knowledge claims, involves not only knowing the relevant conceptual knowledge, but also understanding the ways that communities frame, present, and evaluate evidence within given discourse norms (Bazerman, 1988). Through coordinated and concerted efforts, communities develop ways of evaluating and legitimising forms of evidence in social forums (Longino, 2002). Coming to recognise such patterned uses of language (genres) is part of the learning to do science and engineering. Discourse processes and practices have a dialectical relationship with disciplinary knowledge, as knowledge is shaped by, but also shapes, the patterned uses of discourses to accomplish scientific and engineering tasks (Goodwin, 1995; Kelly, 2014b). In this way, engaging students in epistemic practices of science and engineering serves multiple educational goals (Cunningham & Kelly, 2017b).

This ability requires knowing how to draw from the texts, signs, and symbols of relevant communities and employ concepts in the processes of knowledge construction. In science, writing is a key method for building and distributing knowledge. The use of notebooks and other written inscriptions throughout the process of scientific investigation lead to further written documentation that become objects of discussion and peer review (Myers, 1997). Similarly, in engineering, the uses of notebooks support building and distributing knowledge. The range of audiences in engineering often includes a client for the engineering work.

Research on writing holds the potential to bolster disciplinary learning within science and engineering. The Science Writing Heuristic (SWH) is a tool that supports inquiry investigations through building discussion and negotiation into the writing process (Keys, Hand, Prain, & Collins, 1999). This approach situates argumentation in science inquiry and provides a template that prompts students to construct questions, evidence-based explanations, and reflections of how their thinking has changed over time (Hand, Norton-Meier, Staker, & Bintz, 2009). Rivard and Straw (2000) argued that talk combined with writing enhance retention of science learning over time as talk provides opportunities to share knowledge, ask questions, and build understanding, while writing affords students prompts to refine and consolidate ideas. This view is consistent with others suggesting the need for text diversification so that students use a variety of representations to facilitate their learning processes (Hand, Yore, Jagger, & Prain, 2010). Some of the academic tasks of engineering design challenges are analogous to science inquiry – students propose solutions, test ideas, share and learn through collective activity, and record their data, diagrams, and reflections. In this paper, we examine the role notebooking plays in group design activities to support student development of engineering practice.

Research questions

In this study we drew from a collection of video tapes of elementary classrooms implementing four different design challenges. The design challenges all included the uses of student engineering notebooks. We are interested in the role of these student notebooks in the engineering design activities. In this study we pose two questions:

- In what ways do notebooks structure student learning through engineering design activities?
- What roles do the engineering notebooks play in helping student engage in engineering practices?

Educational intervention and study context

Data for this analysis were collected as part of a large-scale efficacy study of the Engineering is Elementary curriculum. Engineering is Elementary (EiE) is an elementary engineering curriculum that fosters engineering literacy in students in grades 1–5. Each of the 20 EiE units engages students in a particular field of engineering that is related to a science topic they are already learning about in school, ultimately building to a design challenge in which students experience the arc of the engineering design process and develop a technology. The efficacy study included four units:

- *An Alarming Idea: Designing Alarm Circuits (AC)*: This unit introduces students to the field of electrical engineering as they incorporate their understandings of electricity to design AC. During the design challenge, groups are tasked with developing a circuit that triggers an alarm when a water trough for a baby lamb is empty. Students plan a circuit, design it, test it, and develop a schematic diagram. They pass it to another group in the class to construct and test. Based on the results, they improve their design (Engineering is Elementary, 2011a).

- *A Slick Solution: Cleaning an Oil Spill (CO)*: This unit introduces students to the field of environmental engineering as they develop a process for cleaning a model oil spill and explore the effects of oil spills on ecosystems. Groups use a variety of materials as they design and test a process to contain and remove a model oil spill. They consider the cost of the materials and their effectiveness in a second iteration (Engineering is Elementary, 2011b).
- *A Stick in the Mud: Evaluating a Landscape (EL)*: This unit introduces students to the field of geotechnical engineering. They are challenged to use their knowledge of erosion and landforms to make a recommendation about where to install a type of bridge called a TarPul in a village in Nepal. The design challenge asks students consider where the villagers want the bridge to be as well as the shape of the river, the types of soil, and how deeply to anchor the supports for the bridge. They test a model design to failure and incorporate several criteria into their evaluation as they design an improved plan which they propose to the fictional village (Engineering is Elementary, 2011c).
- *Thinking inside the Box: Designing Plant Packages (PP)*: This unit introduces students to package engineering as they utilise what they know about plants' needs to design a package to sustain and ship a plant. In the design challenge, student groups must plan and create a package design that considers basic needs of plants and functions of packages. They then improve and reevaluate this design (Engineering is Elementary, 2011d).

Across the four units, the notebooks structure student investigations that will inform their choice of materials for the design challenge. Guided by questions and data table structures in the notebooks, students sketch their results, document their observations, and are instructed to use their data to make decision decisions. The notebooks also ask students to articulate the materials they will use for their technology, document their reasoning for choosing these, sketch or articulate a design, perform calculations to assess the viability of the plan, record results of their testing, reflect on what aspects of the design worked well or did not, and generate ideas for improving the design. Throughout the notebook student answer open-ended questions, complete data tables, sketch designs, and make recommendations to their clients.

The larger study from with our sample was chosen recruited teachers from Massachusetts, Maryland, and North Carolina. All participating teachers received three days of professional development on the curriculum unit(s) that they would be teaching (assigned based on alignment with which science topics they reported teaching). They then implemented their assigned unit during the 2013–2014 and 2014–2015 school years. As part of this implementation, students completed all written work in an engineering notebook that was returned to the researchers when the unit was completed. The engineering notebooks were developed for the efficacy study by consolidating worksheets already included in the teacher's guides for the units and binding them with a cover and additional blank pages for drawing and writing. The intended student written work, brought together by the notebooks, was designed by the EiE curriculum development team to provide students with a place to collect ideas, organise their work, document and save results of tests (data storage), provide a retrievable record for analysis and redesign, and save information for members of the student groups to share with each other and with other groups. Although every student received a notebook, the EiE teacher guide encourages teachers at many points to have the students write as a class or in small groups and agree on common answers.

Based on interest, location, and availability, a subset of 24 video case study teachers was recruited from the larger study. The team video recorded these teachers' full implementation of the EiE unit (approximately 10 or more hours of teaching per unit per teacher). One camera was focused on the teacher, an additional camera tracked the work of a single group. The teachers constructed the student groups based on their knowledge of the students. The research team asked the teacher to select one or two groups of three or four students to videotape who had parent permission to participate in the study. We expressed a preferences for students of diverse abilities and demographics, who were engaged, and who would not mind the video attention. The camera focused on the group and their workspace, and an audio recorder was set up in the workspace to capture the students' voices.

This study focuses on four video case study classes from the 2013–2014 school year. Our data sources include the videotapes of the teacher and the student group, the student notebooks from those students in the small group, and demographic information we collected about the student, teacher, and school. Because we were interested in the roles notebooks could play in engineering design, we chose one classroom from each of the four curriculum units. In this way, we were able to examine the role of the notebook across four different engineering units. The student groups were selected based on:

- high level of interaction with notebooks, especially in sections related to the design challenge (as determined through mostly or entirely complete notebooks and a cursory examination of group video data), and
- quality of video data for the design challenge (sufficient audio quality for constructing transcripts and camera angles allowing use of notebooks to be observed).

Demographic data were collected from teachers about their students and cross-checked with information collected from students' parents and self-report. Data about the teachers for the four classes are listed in Table 1, and student groups observed are shown in Table 2.

Method of analysis

Our analysis draws educational ethnography and sociolinguistics (Castanheira, Crawford, Dixon, & Green, 2000; Gumperz, 2001; Kelly, 2014b). Educational ethnography examines the cultural practices of a group such as a classroom, as they interact and work together to build common ways of being. We examined classroom video and student engineering notebooks with an interest in understanding how the notebook plays a role in the engineering processes and practices of student groups. As student groups primarily utilise the notebooks not individually, but to write common or consensus responses or record data from group design testing, our analysis focuses on group discussions. The discourse

Table 1. Dataset teachers.

Teacher	Unit	State	School setting	Grade	Race/ Ethnicity	Teaching experience
Ms Glenn	*An Alarming Idea: Designing Alarm Circuits*	MA	Suburb (Large)	5th	Caucasian	3 years
Ms Richmond	*A Slick Solution: Cleaning an Oil Spill*	MD	City (Small)	4th	Caucasian	13 years
Ms Hamilton	*A Stick in the Mud: Evaluating a Landscape*	MA	Suburb (Large)	4th	Caucasian	10 years
Ms Holland	*Thinking Inside the Box: Designing Plant Packages*	MD	City (Small)	3rd	Caucasian	16 years

processes in which students are communicating with each other and through the notebooks necessitate a close look at the ways that texts are inscribed and evoked in conversation. Viewing student group and class activity as cultural practice, this orientation considers the ways that discourse processes shape and are shaped by the constructed norms and expectations; roles, memberships, and affiliation; and everyday ways of being. At the same time, members can reshape and reconstruct these cultural practices. This development occurs interactionally through discourse processes enacted by members of the class, all of whom bring in other cultural practices from their experience with outside groups (Kelly & Green, 1998).

An interactional sociolinguistics approach to analysis starts with initial investigation that seeks insight into recurring group discourse patterns and ways of defining problems (Castanheira et al., 2000; Gumperz, 2001). To examine the patterned uses of texts in the data set, we reviewed videotape of the design challenge in the four classrooms (in total, 16 hours of footage). We transcribed the speech of the teacher and students by speaker turn, paying specific attention to and noting gestures and action associated with the engineering notebooks. Event maps constructed from these transcripts depicted broad shifts in content or style of conversation that mark bounded units as well as logging instances in which speech and action referenced or occurred around use of the engineering notebooks (Kelly, 2014b; Kelly & Crawford, 1997). Analysis of the transcript led us to develop a set of *in vivo* codes focused on the work of the notebook in the small group conversations. Using an iterative process and reviewing our codes, we developed two larger categories for analysis. Through this ethnographic exploration of the data, we identified patterns in the

Table 2. Student groups in dataset.

Student	Gender	Race/Ethnicity
Ms Glenn – *An Alarming Idea: Designing Alarm Circuits*		
Annalise	Female	Black/African/African American
Stephanie	Female	Black/African/African American
Wai	Male	Central/Southeast/East Asian
Ms Richmond – *A Slick Solution: Cleaning an Oil Spill*		
Emma	Female	Caucasian
Henry	Male	Caucasian
Sophie	Female	Caucasian
Ms Hamilton – *A Stick in the Mud: Evaluating a Landscape*		
Alice	Female	Caucasian
Eleanor	Female	Multiracial
Evan	Male	Caucasian
Ms Holland – *Thinking Inside the Box: Designing Plant Packages*		
Amy	Female	Caucasian
Grace	Female	Caucasian
Teddy	Male	Caucasian

usage of notebooks and the roles that notebooks came to play within and across groups and classes during the design challenges.

Findings

Through the process of line by line examination of the instances of notebook usage in the transcripts of the small group interaction, we developed a set of codes representing the roles that notebooks play in the students' engineering experiences, phrased as actions the notebook takes not as a mere tool but essentially as a participant in a group's discourse. We applied these codes to the transcript and revised them as we checked their persistence across the sample. Through successive iterations of the coding process, we arrived at the set depicted in Table 3. Based on these codes, we derived two primary constellations of roles. These categories are that the notebook 'scaffolds student activity' and 'supports epistemic practices of engineering.'

Findings: notebooks scaffold student activity

The presence and content of the notebook structure and scaffold students' activity in the classroom. Teachers rely on the notebook as a tool to remind students what they should be doing and where they are headed within the lessons. Some teachers do this to reinforce students' understanding of the engineering design process. For example, one teacher, Ms Holland, started the engineering design process by having students look at the diagram on their notebooks, asking them 'Which step of the engineering design process, which is so nicely outlined on the back of your [notebook], everybody look, which step have we hit on so far?' (Holland.PP.2). In another classroom, prior to improving their designs, Ms Glenn opened a discussion of the value of improving their engineering designs in a similar way, asking 'If you guys look at the back of your [notebooks], you see your engineering design process, right? Why do we improve?' (Glenn.AC.1879). By pointing to the resources of the notebook, these teachers were able to call attention to the steps of the design process and help students orient their work. In other cases, teachers used the notebooks to help students consider what they will be doing next; for example, Ms Richmond led her students into the individual brainstorming by pointing out, 'You are going to look at page 31 and page 32 on your own' (Richmond.CO.455) to emphasise that they should generate their own ideas before proceeding onto group planning. In these ways, the notebook, along with the teacher guide, *structured teachers' lessons*.

Table 3. Categories and codes.

Category	Code
Scaffolds student activity	Structures teachers' lessons
	Provides reference for student decision-making and consensus
	Provides prompts for students and groups to refocus their activity
	Focuses student attention on relevant details and processes
	Previews future parts of the lesson and design process
Supports epistemic practices of engineering	Prompts students to synthesise and reflect on engineering design
	Provides record of testing information for design evaluation and improvement planning
	Supports communication of ideas to other students and to teacher
	Provides visual reference for development of explanations
	Holds students accountable to plans

Although individual students were each provided with a notebook, much of the work in the design challenges was done as a group. The ways that teachers used the notebooks fostered this; when students in a group planned their design, recorded their test results, and developed improvements, they were expected to reach consensus within the group. Each student documented the shared ideas in his/her notebook. This necessity for a common record pushed students to come to agreement about what to inscribe. To generate one group idea often required students to deliberate, weigh a number of ideas, and provide evidence that convinced their teammates to support their proposal. As they engaged in such discussions, students often referenced data that were provided or that they had previously logged in their notebooks. Thus, the notebook *provided reference for student decision-making and consensus*.

We see the notebook serving in this role in the following exchange (Transcript 1). Here, a fourth grade teacher, Ms Richmond, referred her students to pages 41 and 42 in their notebook, which asked groups to consider further improvements to their oil spill cleaning process design. In doing so, she pointed out the actual work they should be doing (answering the questions in the notebook as a group) as well as emphasised that engineers develop multiple, improved iterations of their designs. At this point in the lesson, students had already created, tested, and improved their cleaning processes. The notebook's questions prompted students to again reflect upon the performance of their solution as they thought about what they might change to improve the next iteration of their design (which they would not actually create). Students in each group were required to reach a consensus regarding which parts of their oil spill process did and did not work well. They then decided which of the evaluative scores they would try to improve in their next design: the cost score, the ecosystem-impact score (how much oil remained on the water after cleanup), or the shore score (how much oil ended up on the shore of the model river).

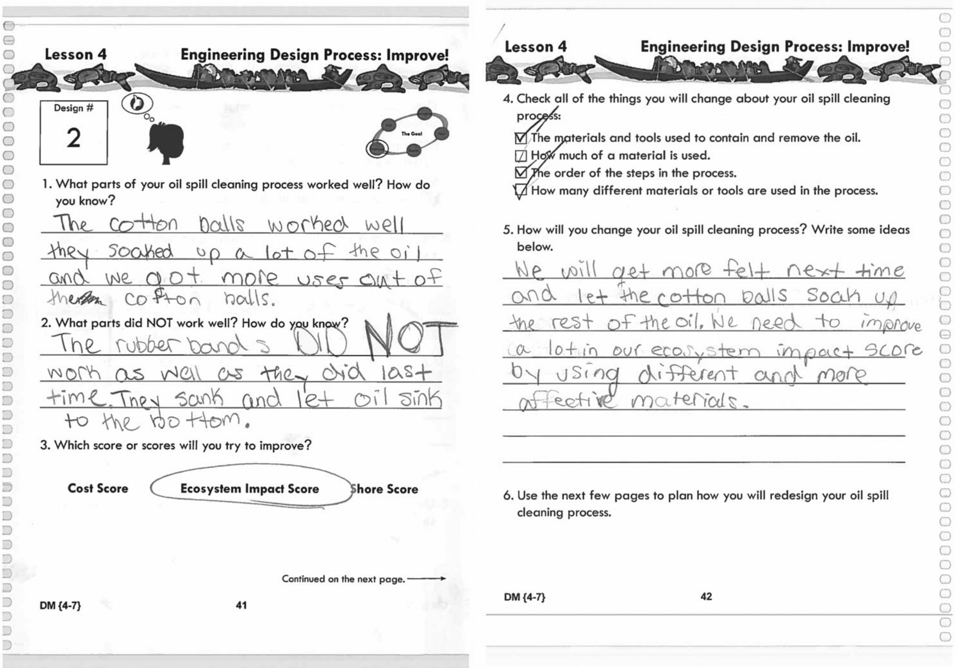
The transcript below shows that the group initially disagreed about what to write. Henry proposed a material that he believed works well – felt (line 1668). Sophie disagreed, and when Emma questioned this, Sophie restated her assertion. In line 1671, she then went on to say that 'I don't think the rubbers bands worked as well as they could have,' explaining her rationale with an observation from the testing. Emma agreed (line 1672), and the two then discussed a material that both felt worked well: cotton balls. They explained why they feel these worked well, relying on observations from their testing (lines 1681–1710), then doing the same in their discussion of what did not work well (rubber bands) (lines 1711–1718). Henry was mostly quiet throughout this and ultimately agreed with Emma and Sophie's answers, indicating that he 'Got it' (line 1719). The discussion of these materials and the amount of oil that the rubber bands left behind in the water appeared to lead Henry to posit that they should be attempting to improve their 'eco-impact score' (line 1722) – examination of the entries in notebooks from the group confirmed that this is the evaluative score that all of them selected.

This episode began with Ms Richmond referring the class to the student notebooks, pages 41 and 42. These pages in the notebook prompted the students with a set to evaluative questions. The group turned to these pages in their notebook. Figure 1 shows the pages from Sophie's notebooks.

Transcript example 1. Ms Richmond. Cleaning an Oil Spill. 1667–1722.

Turn	Speaker	Discourse	Researcher Notes
1667	Sophie:	So, what worked well?	The group starts to discuss.
1668	Henry:	Felt.	
1669	Sophie:	No, I wouldn't say felt.	
1670	Emma:	You thought the felt didn't work well?	
1671	Sophie:	Not really. I don't think the rubber bands worked as well as they could have. They were sinking and letting out oil to the bottom.	
1672	Emma:	Yeah, the rubber bands didn't work as well as last time.	In the previous evaluation, they picked the rubber band as the part of their design that worked the best.
1673	Sophie:	Let's say …	Reviewing the materials in their design.
At this point, the group was asked to clean their desks. The teacher removed the model oil spill and asked the students to wipe down the desks to remove water and oil. The group reminded her that they also needed to give her their oil spill indicator readers (a laminated sheet that acts as a tool to measure the amount of oil remaining). They did so, and the teacher reminded the class to keep their coloured lanyards on as they clean up (the lanyards assisted videographers in identifying groups).			
1681	Sophie:	Okay, let's say the cotton balls. The cotton balls worked well. We're saying the cotton balls worked well.	The conversation broke briefly as the group needed to clean up their work area
1682	Henry:	She said on 42.	He is looking in the notebook between page 41 and 42
1684	Sophie:	I'm saying the cotton balls worked well because they soaked up a lot …	Starting to write in her notebook as she talks
The group takes a break to wash their hands with paper towels from the teacher, then gathers the rest of their materials that need to be returned. They move the microphone to make sure they don't get water or oil on it as they wipe up the rest of their table, then return to their discussion.			
1708	Sophie:	We got more uses out of them	Another break as they clean up more with teacher assistance, then back to discussing
1709	*Teacher:*	*Guys, don't move.*	*To another group*
1710	Emma:	And didn't let it go out. Picked up oil, and didn't push it out. Cotton balls.	Agreeing with Sophie and writing as she talks
1711	Sophie:	So that's it. The rubber bands …	Moving to next question
1712	Sophie:	Did not work well.	
1714	Sophie:	They sank …	The whole group is writing
1715	Emma:	Yep. They sank and let out some of the oil.	
1716	Sophie:	They sank and let out …	Writing as she talks
1717	Emma:	Some of the oil.	Emma writes
1718	Sophie:	And let out some oil leaking to the bottom.	Finishing writing
1719	Henry:	Got it.	Henry has been following along and finishes writing
1720	Sophie:	And let oil sink to the bottom.	Looking at Emma's notebook
1721	Emma:	Yeah.	Finishes writing
1722	Henry:	Definitely a eco-impact score.	Circles 'Ecosystem-Impact Score' in notebook

Here we see the way in which the notebook *structures teachers' lessons*, allowing Ms Richmond to refer to it to organise her lesson and guide children's work. The need to write an answer, a collective answer across the group, in their notebooks, meant the students were required to discuss what they thought and then agree upon what these data suggest their next step in improving their oil spill cleaning process might be. Sophie, Emma, and Henry relied on the notebook to *provide reference for their decision-making and consensus* (turns 1682, 1684, 1714–1722). By asking them to focus on what did and did not work well, the questions in the notebook scaffolded the group's progress towards picking the ecosystem-impact score as what they would like to improve. Their conversation that followed this one further built upon this line of thought – in the notebook they each recorded their group decision to add more of the cotton balls that they felt worked so well to the improved design.


Lesson 4 Engineering Design Process: Improve!

Design # 2

The Goal

1. What parts of your oil spill cleaning process worked well? How do you know?

The cotton balls worked well they soaked up a lot of the oil and we got more uses out of the cotton balls.

2. What parts did NOT work well? How do you know?

The rubber bands DID NOT work as well as they did last time. They sank and let oil sink to the bottom.

3. Which score or scores will you try to improve?

Cost Score Ecosystem Impact Score Shore Score

Continued on the next page.

DM {4-7} 41

Lesson 4 Engineering Design Process: Improve!

4. Check all of the things you will change about your oil spill cleaning process:

☑ The materials and tools used to contain and remove the oil.
☑ How much of a material is used.
☑ The order of the steps in the process.
☑ How many different materials or tools are used in the process.

5. How will you change your oil spill cleaning process? Write some ideas below.

We will get more felt next time and let the cotton balls soak up the rest of the oil. We need to improve a lot in our ecosystem impact score by using different and more affective materials.

6. Use the next few pages to plan how you will redesign your oil spill cleaning process.

DM {4-7} 42

Figure 1. Sophie's oil spill notebook page 41–42.

The notebook also played a role in getting the students quickly back to their conversation after needing to break and clean up their model oil spill (turns 1673–1681 and again turns 1684–1708); it *provided prompts for students and groups to refocus their activity*. The students were held accountable to the task they were to accomplish by the notebook – the need to document their decisions and next steps in the notebook oriented the students to refocus on their engineering design process. Evidence of this refocusing role of the notebook was present across the four groups we studied – for example, in the plant package group, Grace ended a lengthy discussion with her group about the branding on the label for their plant package by referring to the package durability results they recorded in their notebook: 'Did we get a 1 or 2 on our shake test?' (Holland.PP.2260).

Teachers, too, used the notebooks to reorient students who had been sidetracked by off-topic discussions, or who had failed to record their ideas in the notebooks as they discussed them, as Ms Glenn's teacher aide does by telling her group 'So you guys need to start drawing [your alarm circuits]' (Glenn.AC.981). This scaffolding of students' activity through the need to document the outcome of concrete steps they were to accomplish allowed students to more easily return to the actual work of engineering.

In the oil spill transcript above, we also see Sophie, Emma, and Henry deliberating about the materials that are available to use in their designs. They could have considered a variety of aspects of their oil spill cleaning process, including the order in which they used these materials or the physical way that they implemented the model tools. The notebook and its questions pointed them to think about their choice of materials, and the trade-off between their effectiveness and cost. This is an example of how the notebook *focused student attention on relevant details and processes*. In all of the design challenges, there were many variables students could attend to when planning and improving their designs, but the scaffolding of the notebook directed them to those that are most important.

We also see how the notebook can guide students' attention in the class that worked as geotechnical engineers. After students in Ms Hamilton's class developed and improved their plan for where to put a TarPul bridge over a river in a Nepalese village, they concluded the unit by writing a speech or letter to the people of the village explaining their choice (Transcript 2). Although students could write about many of the factors that went into their decision-making process, the notebook (page 48) specifically pointed students' attention to explaining their reasoning behind the location they chose for the bridge and their recommendation for the amount of soil compaction around the bridge's supports:

Write a persuasive speech to the village elders to explain to them why you think your selection is the best site for building the TarPul. In your speech, include the following points:

- Which site you have selected.
- Why you think this is the best location for building the TarPul.
- The amount you recommend compacting the soil around the TarPul foundation.
- Why you believe that this is the best amount of compaction for building the TarPul foundation.

In this way, the notebook focused the students' attention on the important aspects of the engineering at hand.

Evan and Eleanor followed the notebook's suggestion and talked through what they were writing. They referred to data stored in the notebook as they articulated the advantages and disadvantages of bridge locations and soil compaction. The final report that Eleanor created in her notebook can be seen in Figure 2. The conversation, and the letters they wrote in the notebook, demonstrate that these students understood the relationship between the science of the types of soil and stream's erosion of the earth and the engineering recommendations they offered about where to site the bridge.

This pair (their third group member, Alice, was absent this day) started by clarifying why the villagers' first choice of location (site D) may not be ideal when viewed through a scientific/engineering lens; Eleanor explained that a bridge at that location would be 'on a river bend and will erode more' (line 783). They then make a case that this was not true of their recommended location, site E, as a bridge here 'will erode less,' according to Evan (line 786). Eleanor wrote that they can compact the soil at their chosen location (line 787), and Evan added that doing so meant the support poles for TarPul bridge 'will be straight and strong' (line 790). To emphasise that their site E will be more effective than the villagers' choice, they also discussed and wrote about how the nature of the 'rocky soil on one side and organic on the other' (line 793) at site D meant that the 'TarPul will be leaning down on one side … it would not be straight enough' (line 799). This demonstrated that they understood how the types of soil affected the efficacy of supporting a TarPul pole. Returning to focus on soil compaction and its role in making looser soil more stable, Eleanor wrote that 'we can compact the soil but it will not be as safe' (line 803), to which Evan adds 'as safe and sturdy' (line 804).

Transcript Example 2. Ms Hamilton. Evaluating a Landscape. 781–806

Turn	Speaker	Discourse	Researcher Notes
781	Eleanor:	Let's say, the site we've picked … is only 1 site away from where you want it to be. The site you want is …	Throughout, they are both writing as they talk and finishing each other's sentences. They explain that their recommended site E is very close to the villagers' site D.
782	Evan:	So from where you want it to be at?	
783	Eleanor:	Your site … The site you want is on the river … bend. The site … on a river bend and will erode more.	Explaining the potential erosion of the villagers' site D
784	Evan:	Yup. River bend and it will erode more.	
785	Eleanor:	So site E, we recommend is on a straight part of the river, and will erode …	Contrasting the villager site to their recommended site
786	Evan:	Less … and will erode less. Okay.	
787	Eleanor:	We can compact E's soil and will make the …	Focusing on soil compaction
788	Evan:	Soil and it will make …	
789	Eleanor:	The … pole attached to the TarPul up. The poles holding the TarPul up …	The TarPul bridge is supported by two poles stuck into the soil.
790	Evan:	Holding the TarPul up will be straight and strong.	Focus on effects of soil compaction for the bridge
791	Eleanor:	.. and strong … Wait I'm going to say … So site D will fall …	Looking quickly back in notebook to the map to confirm soil types
792	Evan:	Where you want the TarPul to be …	
793	Eleanor:	Is on rocky soil on one side and organic on the other … your … TarPul will be … leaning …	Reporting soil types as a reason against the site
794	Evan:	Yeah …	
795	Eleanor:	Diagonal … leaning diagonally? Leaning down?	
796	Evan:	Yeah, leaning. Leaning down. Why?	Effects of soil on bridge
Break covers microphone picking up offscreen chatter from another group discussing an upcoming birthday.			
799	Eleanor:	Tarpul will be leaning down on one side … It would not be straight enough.	Break covers another group talking offscreen.
800	Evan:	On one side … on one side and will not be straight enough.	
801	Eleanor:	No, we will compact it but will still not be straight enough. We can compact the soil … but	Erases previous few words to include compaction
802	Evan:	We will what?	
803	Eleanor:	We can compact the soil but it will not be as safe and …	
804	Evan:	It will not be … as safe and sturdy as	
805	Eleanor:	As site E … At least that's what I'm saying.	Finishes writing
806	Evan:	Okay.	Finishes writing

We see Eleanor and Evan discuss and write about many factors that support the recommendation they made for a site. They ultimately focused on the possible problems due to erosion of their site and the villagers' alternate choice, as well as the potential for soil compaction to reinforce the sturdiness and safety of the TarPul bridge. The notebook, and in particular the prompt for the speech, *focused their attention on relevant details* that can help make their recommendation more persuasive. This focus helped the pair decide what should, and should not, be included in their argument to the villagers about their recommended bridge site. They needed to agree on what to write, as they would be reading the speech in front of the class. Analysis of their responses in their notebook proved that they were indeed writing the exact same speech that they later gave. This common record allowed them to help their absent group member, Alice, to catch up

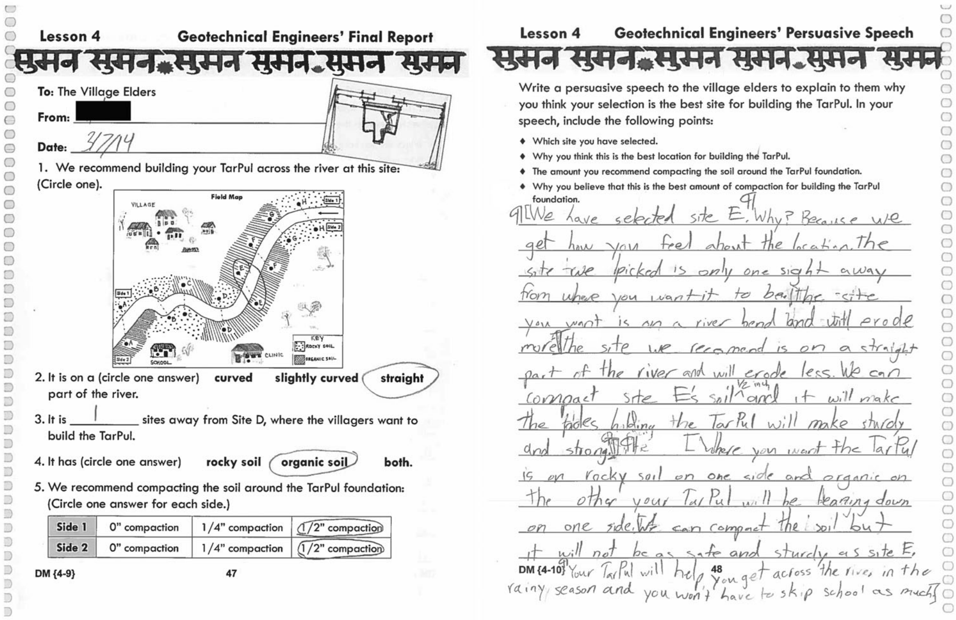


Figure 2. Eleanor's Tarpul notebook page 47–48.

quickly before the public presentation. Thus, once again, the notebook also serves to *provide reference for their consensus.*

While the notebook provided teachers a way to orient students to where they should be and what they should focus on, it did not constrain students merely to what they were doing that day. The notebook contains all the lessons for the unit and thus it *previewed future parts of the lesson and design process for students.* In some cases, this foregrounded the arc of the engineering design process, like when Ms Glenn told her class as they looked at their notebooks, 'When we start today, we are going to start with Ask, and we are going to go through the process. Ask, Imagine, then we're going to Plan, then we'll Create and then we'll Improve.' Looking at the diagram of the steps on her notebook, Annalise asked, 'We're going in order?', as she strove to understand the scope of the next few days. Ms Glenn did not disagree but focused her on the day's work as she explained, 'the only step we are not doing today is Improve' (Glenn.AC.96–98). In other instances, this knowledge of future information cued students to criteria or constraints that they had not yet discussed, potentially impacting imagined ideas and decision-making. For example, even before brainstorming initial designs for their PP, Grace and Teddy looked ahead and found that material cost would be a factor in their engineering: 'I know how much everything is!' Grace said, and Teddy responded, 'Me too. I turned and I looked in the back back back back back page' (Holland.PP.143–144).

There were two ways that the notebooks evoked student activity. Some roles were inherent to the intended procedures of the curriculum. Others emerged from students' activity. Three of the scaffolds were inherent to the engineering tasks organised by the curriculum lessons. These three scaffolds – structuring teachers' lessons, providing prompts for students and groups to refocus their activity, and previewing future parts of the lesson and design process – each were designed to support engineering design processes. The other two scaffolds – providing reference for student decision-making and consensus, and focusing student attention on relevant details and processes – were emergent and occurred when students took action not prescribed by the curriculum or teacher. In this second way, the notebooks served to provide students autonomy to engage as engineers in the activities. This is a productive use of written discourse to support engaging in the epistemic practice of engineering.

Findings: supports epistemic practices of engineering

The use of engineering notebooks by professional engineers is commonplace – engineers are often trained to document their trials, results, and thoughts in their notebook so they can provide a record of their data and tests. In the real world, the notebooks can be called upon as a source of evidence in altercations involving intellectual property and testing results. Students' use of a notebook can also support their engagement in epistemic practices of engineering, particularly those that focus on communication and using evidence (Cunningham & Kelly, 2017b). Epistemic practices are the ways members of a discipline communicate, assess, and legitimise the outcomes of their work (Kelly, 2016). In engineering, these outcomes can include knowledge that they produce, technologies they create, accepted methods for doing engineering work, and ability to satisfy clients' needs.

In Eleanor and Evan's exchange above, writing the speech in the notebook did not just focus them on the important factors of the design challenge, but required them to consider everything they have learned during the unit as they crafted a persuasive argument for their design. In doing so, the notebook *prompted students to synthesise and reflect on engineering designs*. For Eleanor and Evan, this meant recalling what they now knew about erosion, soil types, soil compaction, and how these all impact the structural integrity of the TarPul bridge, using all of this as evidence for their recommendation as mentioned above. Through the work of engineering, these students engage in the epistemic practice of balancing multiple criteria and constraints and they generate a recommendation.

In their discussion about which materials worked well to clean the model oil spill, Sophie, Emma, and Henry reflected on the fact that their rubber bands were one of the best parts of their initial design but did not work at all in their improved design. Needing to reconsider their materials as they wrote a plan for a hypothetical third design, they needed to reconcile this anomaly as they decided whether they should continue to include the rubber bands or not; it prompted Sophie to think back on the design, and she realised that the disparate data might be due to how they used the rubber bands – 'I think we stretched them differently' (Richmond.CO.1933). Her process of reflecting on how uncontrolled testing led to two different results for their design would not have been initiated had the group not had to determine what they would write in the notebook.

This exchange also demonstrated how the notebook *provided a record of testing information for design evaluation and improvement planning*. This practice occurred across the design challenges and groups we studied; by holding the information from previous tests, students could remind themselves what they were thinking, particularly when the design challenge took place across multiple classroom days. The group that was engineering plant packages (PP) found that their improved design received the same overall score as their initial design. They were initially at a loss as to how they could potentially increase this score. However, as she looked back at her notebook, Amy reminded the group that they were actually thinking they could get a better score if they altered the soda bottle that was the base of their package, reporting that 'we wanted to change the way it was cut,' a process that would have necessitated teacher assistance and approval (Hamilton.PP.1401).

The work that students did in the notebook across the design challenges *supported communication of ideas to other students and to teachers*. Some challenges featured more formalised communication and presentations like the one that Eleanor and Evan prepared for, but the notebooks of all of the challenges featured a section where students needed to draw individual designs and then discuss their strengths and weaknesses as they to develop a singular group plan. The design of the notebook here supported and invited communication between students. First, the notebook asked all students to brainstorm and document their individual ideas – each student had the opportunity to think creatively and capture his/her ideas at his/her own pace. Next students needed to generate a single, initial idea about the design of their technology. To do this, students shared their individual ideas and thoughts with their group. They needed to figure out how to explain the features of their own challenges to other group members in words or by referencing the models and sketches they had drawn.

We see the interplay between one's own ideas, captured in notebook sketches, and a group plan in the group doing the electrical engineering challenge. Annalise, Stephanie, and Wai brainstormed their own ideas for an alarm circuit (Transcript 3). They needed to coalesce these into a group plan in the form of a schematic diagram that represented the group's circuit. Supported by the teacher aide, Stephanie and Wai discussed where to put the lightbulb on the drawing (turns 1002–1004). The group addressed the fact that their current proposed design has two batteries and may have the potential to start a fire if this overpowers the circuit (turns 1005–1015). They opted to remove the battery and accepted that, as Annalise says, 'we don't have to use all our tools' (turn 1017). Annalise expressed confusion about where to put the foil in the design (turn 1019–1020). They then encountered an issue of whether the symbols they were using are accurate across the group, with Stephanie telling Wai that his drawing was incorrect leading him to alter it (turns 1021–1023). Wai helped Annalise understand how the wires should be put into the design by indicating on the drawing in her notebook, which helped communicate his idea (turns 1026–1030), and which was reinforced by the teacher aide (turns 1031–1032). The aide then asked the group about connecting the wires for the switch that they needed to incorporate, once again referring to their drawings (turns 1033–1035). Wai quickly developed a physical model using two nearby rules to help get his idea across, dropping one of the rulers to touch the other one and saying 'Annalise, pretend these are two wires, right? When it falls down, it touches like this' (turn 1036). By the end, with the help of the schematic diagrams they created in their notebooks, everyone had come to consensus and they returned to the issue of where to put the lightbulb in the design (turns 1040–1042).

Transcript Example 3. Ms Glenn. Designing AC. 1002–1042

Turn	Speaker	Discourse	Researcher Notes
1002	Stephanie:	Let me ask you something. Where are we going to put the light bulb? Where are we going to put the light bulb?	Stephanie pushes on Wai's initial plan for a circuit and points to her drawing.
1003	Wai:	I don't know.	
1004	Stephanie:	I'll just put it right here. The light bulb goes right here.	She picks a spot in her diagram and draws the bulb
1005	Aide:	We have to make sure that we only … We don't start a fire.	Students were warned earlier about short circuits and fires
1006	Annalise:	Oh yeah we have to make sure we don't start a fire.	
1007	Wai:	How about only one battery?	
1008	Aide:	Oh this is for the schematic drawing. The foil and stuff goes on here. That's okay. You can draw around it.	The aide points to indicate that Annalise has drawn her diagram in the wrong spot on the notebook
1009	Wai:	How about only one battery?	
1010	Aide:	Yes. Why is that Wai?	
1011	Annalise:	The foil goes here.	Annalise is drawing the schematic diagram that incorporates materials like foil, not just wires
1012	Stephanie:	But we have two batteries.	Looking at her diagram
1013	Aide:	Listen to Wai.	
1014	Wai:	We can use one. Because if we use two we might start a fire because there is too much power going around.	
1015	Aide:	Because look at this. How you guys had that …	Pointing to diagram
1016	Wai:	Like we don't have to use all of it.	
1017	Annalise:	We don't have to use all our tools.	
1018	Aide:	Right.	
1019	Annalise:	So we put the foil thing, then after that …	Pointing to her notebook
1020	Annalise:	But how? How?	Looking at her diagram in confusion and speaking to the group
1021	Stephanie:	You're not supposed to draw it like that.	Indicating Wai's representation of the foil
1022	Wai:	Like this.	He adds a mark
1023	Annalise:	Oh that. Okay. The clip. Clip. Okay. I don't know, we don't need that.	Drawing
1024	Wai:	Yeah we don't need that.	
1025	Annalise:	Then after that we put …	
1026	Wai:	Two. Like the two wires on the bottom stay here and when they go down they touch.	He indicates on his drawing and the others copy it down
1027	Annalise:	Wire. Wire where? Where does the wire go?	As she draws
1028	Wai:	Two wires … And two wires.	He leans over and points on Annalise's drawing
1029	Annalise:	Oh two wires here?	Pointing at the spot on her drawing
1030	Wai:	Yeah.	Nodding
1031	Aide:	You can connect it.	
1032	Wai:	Yeah.	
1033	Aide:	So where are you going to connect the wire?	
1034	Annalise:	Connect the wire to the what?	
1035	Aide:	How is the … What is this going to touch?	Pointing to Annalise's diagram
1036	Wai:	The wire. Pretend … Annalise, pretend these are two wires, right? When it's fall down, it touches like this.	He holds up two rules to visualise the switch mechanism
1037	Annalise:	And then the thing lights up.	
1038	Wai:	Yeah.	The others are drawing
1039	Aide:	Okay.	
1040	Annalise:	Where is the light bulb going to go?	
1041	Wai:	Anywhere. I don't know.	
1042	Annalise:	Light bulb … It's like a mushroom. A mushroom bulb.	Describing the lightbulb symbol as she draws

The critical role of the notebook in holding students' graphical ideas was made clear in this episode. Because they documented their ideas in concrete drawings, the students were able to refer to these to help clarify their thinking and communication as they work through the elements of their design. The need to settle upon one group idea meant that Wai, Annalise, and Stephanie needed to communicate with each other to understand the design that they were jointly proposing. The notebook *supported communication of ideas to other students* and, in this case, also to the teacher aide. The abstract nature of the design, as communicated through the schematic diagram, however, also meant that the drawings were integral to this communication strategy. Without the notebooks, Wai would have been unable to get his thoughts across; he pointed to the drawings of his group members to explain his idea – when this was not enough he reverted to gesturing with rulers to depict motion. The notebook did not merely support communication, but specifically *provided visual reference for development of explanations*. When showing their individual ideas for plant package designs, Amy's group also relied on their drawings to explain; her description of her idea incorporated the visual aid of her sketch. After she explained, pieces of her sketch were incorporated into the shared group design (Holland.PP.390). In these instances, communication and use of symbols are epistemic practices that engineers routinely rely upon to move forward with their design.

In the process of writing down their plans to communicate to their group and to their teacher, the students were also committing to a specific plan that they would test. They needed to be clear in their description, because by agreeing to a group plan and documenting it, the notebook could *hold students accountable to plans*. Once a 'final' design was agreed upon, students were expected to stick with it throughout the entire testing cycle. A natural instinct of students is to tinker should the design show the possibility of failure; however, this does not permit accurate data collection and analysis. By anchoring students in one design at a time, children can undertake analysis and then generate revisions to improve their design. In the alarm circuit unit, students developed a plan that is handed off to another group to design and test, just as technologies are often created in the real world. This division of labour reinforced the need to work according to the specifications so all groups were clear on what was expected, constructed, and tested.

The importance of sticking with the plan was also experienced by the group cleaning the oil spill. During their initial testing, Emma, Henry, and Sophie improvised on the plan they put forth, which resulted in them far exceeding their budget due to repeated use of some costly materials (Transcript 4). In their improved design, Sophie diligently and repeatedly checked their plan as they tested to ensure this didn't happen again, even when Henry wanted to add a second rubber band that was not included in their plans. Henry suggested this (turn 1522), but Sophie pushed back, referring them to the plan (line 1523). While Sophie prepared to test a cotton ball, the next item in their plan, Emma and Henry were distracted by potentially improvising with the felt (lines 1524–1530). Catching wind of this, Sophie once again pushed the group to stick to the plan they wrote down (line 1531). While Emma seemed to remember a plan involving folded felt (line 1532), the notebook provided Sophie with the evidence she needed to keep them on track (line 1533).

Transcript Example 4. Ms Richmond. Cleaning an Oil Spill. 1522–1533

Line	Speaker	Discourse	Researcher Notes
1522	Henry:	We need the other rubber band. We need to use the other rubber band.	
1523	Sophie:	No, we said we would do that earlier. We can't do it now.	Checking the plan in her notebook
1524	Emma:	Yeah, we have to take it out and see. Where is it?	Referring to the felt, which is one of the next materials
1525	Sophie:	I don't know.	
1526	Henry:	Oh, here it is.	
1527	Sophie:	Don't use the felt yet. We're not going to be able to use the felt yet. Okay? All right, first, let's do this. What I'm going to do is I'm going to go down, one, and to make it touch the bottom.	Prepares to test using a cotton ball, the next material in their process
1528	Henry:	Just clip that off.	To Emma as she prepares the next material
1529	Sophie:	Ready? One.	Testing
1530	Emma:	Well, we can use the felt.	
1531	Sophie:	Wait, what did we say to do?	Reminding the group to stick to the plan
1532	Emma:	We said we would fold …	Not looking at notebook
1533	Sophie:	No, we didn't say we would fold it.	Looking at her notebook

Without the notebook and the documentation of group decisions that were reached, Sophie would not have been able to direct the group to refrain from improvising and repeating the cycle of exceeding their budget by adding costly uses of materials to their process. The notebook *held the group accountable to their plan* and thus supported the students' engineering design practice. It also allowed them more accurately use the results of their testing by *providing a record of testing information for improvement planning* that the group later referenced while debating which of the materials did and did not work well.

There are two ways notebooks supported students' engagement in epistemic practices of engineering – those concerned with communication of knowledge claims and those initiated by the students to reflect on such knowledge claims. Three of the supports for epistemic practices – providing a record of testing information for design evaluation and improvement planning, supporting communication of ideas to other students and to teacher, and providing visual reference for development of explanations – focus on the importance of sharing data records, inscriptions, and schematics for proposing, communicating, and evaluating knowledge claims (Kelly, 2011). Two other roles – prompting students to synthesise and reflect on engineering design, and holding students accountable to plans – were more emergent and required students to take specific actions. These examples show how through engagement and the construction of appropriate classroom norms, students are capable of evoking written texts for epistemic purposes in engineering design.

Discussion

Our analysis of students' interactions across four engineering challenges surfaced a number of roles student notebooking played to support student engagement in engineering. Both students and teachers used the notebooks to scaffold student activity; it provided prompts and structure to organise and order the activities of the students. As it did so, it also asked students to engage in some of the epistemic practices of engineering such as synthesising multiple types of data to inform a design, recording and reflecting upon data, holding students accountable to their data and plans, and communicating recommendations to a client. Across the categories of supports for student activity and for the uses of epistemic practices of engineering, three discussion points emerge relevant to writing in pre-college engineering: *uses of prompts to engage students in effective uses of writing*, *the role of the notebook in the students' small groups*, and *the ways design challenges support motivation for writing*.

Elementary aged students need prompts to guide their use of notebooks. Professional engineers' notebooks are blank books. Understanding what to put into these is a practice that is built through apprenticeship and experience. Students need scaffolds to organise their activity and draw their attention to salient features. For example, in the oil spill unit, the notebooks (p. 32) structured the process that students developed for removing oil by listing Step 1, Step 2, and Step 3 and asking students to indicate for each what their goal was (containing or removing the oil) and what materials and tools they would use in that step. Young writers often need explicit prompts to organise their ideas. With this in mind, engineering notebooks were developed for each of these design challenges. The intended goal was that these notebooks to guide student activity in a manner that developed some independence from the teacher and allowed students to explore divergent ideas and designs. By providing data tables, asking them to record certain types of data, comparing the results of their individual designs, requiring they reflect upon their data and draw conclusions, and mandating that they reach a group consensus which they record before proceeding to the next activity, the student activity and interaction was scaffolded to support learning. This is especially true for young learners where the focus on hands-on activity may distract from the cognitive goals of creating knowledge through engineering design. Importantly, the scaffolds built into the notebooks needed to be realised through the discourse practices and classroom norms. In this way, the notebooks stored evidence for conversations. Classroom pedagogical norms and expectations that students would refer to their notebooks as they constructed explanations ensured that students used this written information.

Through reference by the teacher and use by the students, the notebooks took on a role as member within the small groups. Our video analysis of the student group and their work with notebooking demonstrated how the notebooks took on a role as a group member. These notebooks served not just a tool, but essentially a participant in the discourse by guiding student activity. The prompts provided by the notebook afforded students opportunity to discuss, deliberate, use evidence, and explain their thinking. Importantly, the opportunities to make reference to, draw from, and employ the written work from the notebooks was supported by classroom norms. The curriculum was designed to establish norms, similar to professional engineering practices, that valued learning and sharing across groups, building evidence to support design challenges, and evaluating the engineering products based on multiple criteria and constraints (Cunningham & Kelly, 2017a). Such curricular goals are meaningless without fidelity in the implementation. The video analysis provided evidence that the teachers were able to establish classroom and conversational norms for interaction that valued student collection decision-making, sharing of ideas from individual students and from the consensus of student groups, respect for evidence, and attention to alternative solutions. The video data of the classrooms, including verbal and gestural interactions, made such norms visible to the participants and analysts alike. These norms were only partially visible in the physical artefact of the notebook – they were constructed, interpreted, and communicated through the talk about the written texts, as was apparent in the videos of students and teachers at work. Thus, the role of the notebook was only a potential until evoked and brought into the conversations, within the discourse norms of the classrooms. For example, the recording of materials for the plant package during the planning phase was referenced by team members as they constructed their package. The notebook reminded group members which materials, and in which configurations they wanted to use them, thus acting as a voice during the deliberation and decision-making. This voice was valued by the students as they needed to use information (in this case, the science of plants) in the plans.

A key piece to developing competency in disciplinary discourse is the use of relevant practices through purposeful activity. Students need reasons to engage in such discourse. The engineering design challenges offered students opportunities to draw on and use their science and practical knowledge to solve problems. This allowed students with ways of knowing to communicate. Such communication took the form of verbal discourse, including gesture, as well as written forms of communication such as diagrams, tables, and descriptive and persuasive texts. The unique designs of the student groups may motivate students to write, as they have reasons to share their knowledge to accomplish the tasks. Thus, writing was integrated in the on-going activity of the student groups and was motivated by the unique features of the design challenges. For example, in many of the units, including the alarm circuit unit, the notebook asks students to reflect upon the results of their tests to consider what they might change in the next iteration. Students were asked which parts of the circuit need to be improved and how they know. After they wrote a textual response, students were asked to 'draw a schematic diagram of your improved alarm circuit. In the box below, draw a labelled diagram of your improved switch connection point' (p. 30). Students want to improve their designs and usually readily share their ideas. The uses of written texts (in this case schematics) was motivated by the next step in the design challenges. Each student group was required to invent a schematic representation that was sufficiently detailed and comprehensible that another group could (and was required to) use the schematic to build the circuit in question. In this way, students were asked to 'talk, write, and draw' science and engineering in ways that used scientific concepts to solve real problems. Thus, the writing tasks were not only valued by the teachers, but also by the students as they sought to improve their engineering designs posed by the challenges.

Conclusion

Students' engineering notebooks in design challenges played important roles in the ongoing and emergent activity of the student groups and classroom cultures. The prompts and discourse in these classrooms framed how written texts, inscriptions, and schematics were used through engagement in epistemic practices of engineering. Reciprocally, the students' written texts, inscriptions, and schematics provided bases for, and shaped the development of, the discourses processes of the classrooms. The notebooks took on roles scaffolding student work and supporting engagement in epistemic practices as related to the educational goals of learning science concepts, applying the engineering design process, and developing identity as learners of engineering. Further research into how to support student engagement in epistemic practices of science and engineering through the use of spoken and written discourse practices needs to consider the myriad of ways that students make sense of disciplinary knowledge. As engineering becomes a more common discipline in elementary classrooms, it is essential that we gain a better understanding of how to structure design challenges and incorporate the use of engineering notebooks and other strategies and artefacts that successfully engage students in authentic engineering practice.

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