Teachers’ attention to student thinking during the engineering design process: A case study of three elementary classrooms

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Introduction and Previous Research

While various fields of engineering, engineering curricula, and educational frameworks may invoke different representations of the engineering design process (EDP), design is undeniably central to the work of engineering, and thus essential to the education of professional engineers. A number of studies have investigated the engineering design process for college students and professional engineers. Recent shifts in K-12 STEM standards have instigated discussions of exactly what engineering content and methodologies belong in elementary and secondary classrooms, and if the EDP is to be included in these standards, researchers must learn what K-12 teachers who will be teaching engineering understand about it, and how they incorporate the process into their lessons in order to design appropriate curricular supports and resources.

Interviewing or surveying teachers about their knowledge of EDP is one way to accomplish this, but including data from an actual enactment of an engineering lesson in the teachers’ classrooms provides a more robust look at teacher understanding and practice. Our guiding research question becomes: how do teachers direct their attention and respond to students during the enactment of a lesson utilizing the engineering design process?

This paper presents a case study of three elementary-school teachers (grades 1, 3, and 5) who enacted an introductory engineering lesson asking students to define engineering and then complete an engineering design challenge. Through transcript excerpts and a teacher attentional skill framework, we present a view of the engineering design process in these classrooms, with comparisons across the three grade-levels and teaching styles. The interview and classroom data were analyzed using a framework from Ainley and Luntley designed to identify the attentional skills of mathematics teachers responding to student thinking. Ainley and Luntley’s theoretical model of expert teaching practice contends that proficient lesson planning or Shulman’s pedagogical content knowledge, for example, are not the only predictors of teaching skill; in order to characterize a teacher’s performance minute by minute in the classroom, one can examine her practice with regard to attention-dependent knowledge, through a framework for attentional skill produced by their study (found in Table 1).

According to Ainley and Luntley, attention-dependent knowledge includes a “repertoire of attentional skills for attending to cognitive and affective aspects of pupil activity which may not be apparent to those without this experience” and contains knowledge which “cannot be written down…[but] becomes available during the complexity of the progress of a lesson, often in response to instances of pupil activity that could not be predicted on the basis of the teacher’s subject or pedagogical knowledge” (p 4). Thus the framework they used to identify this knowledge and the data presented in this present study rely on both classroom observation data as well as later teacher reflections on their practice. Additionally, the emphasis Ainley and Luntley place on teacher attention to student thinking during the lesson, as opposed to rigid prescribed lesson planning, correspond neatly to the need for teachers to be flexible and responsive to student needs while engaged in open-ended problem solving of the kind found in
The results of this study are presented through the various steps of the EDP, and lead to suggestions for K-5 professional development as well as directions for further research on student engaged in the engineering design process.

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<tr>
<th>Concept</th>
<th>Code</th>
<th>Description</th>
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<tr>
<td>Characterizing the object of attention</td>
<td>affective/behavioral</td>
<td>The underlying focus of episode, from an observer’s view; a problem being the teacher addressing the students’ differing concept, and an opportunity being the teacher trying to extend the students’ thinking.</td>
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<td></td>
<td>cognitive problem</td>
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<td>cognitive opportunity</td>
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<td>Characterizing the purpose to which the</td>
<td>interrogating student</td>
<td>From classroom transcripts as well as teacher reflection; interrogating the focus of students’ attention to move their thinking forward, versus merely noting but not addressing it</td>
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<td>attention is put</td>
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<td>noting pupil attention</td>
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<td>reaction (a familiar</td>
<td>Useful to have teacher reflection on whether the strategy was often used, a reaction, occurring repeatedly over the lesson, or a response, adapted to the context of the particular episode</td>
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<td>Characterizing the teachers’ perspective of</td>
<td>conceptual</td>
<td>Based on the teachers’ recall of the episode during the interview; whether the teacher was conscious of making a conceptual choice in that particular episode, or not being aware of their choice at all</td>
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<td>the attention</td>
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*Table 1. Adapted from Ainley and Luntley’s framework for mathematics teacher attentional skills.*

Methodology

**Participants:** The teachers involved in this study represented a variety of grades, experience levels, and educational specialties, and the case studies below are meant to reflect that. The teachers were invited by their principal to participate based on their perceived willingness and interest to engage in education research, and to cover the range of the elementary-school grade levels. Table 2 below shows the participants and their background and experience.

<table>
<thead>
<tr>
<th>Teacher Participant</th>
<th>Grade-level</th>
<th>Teaching experience</th>
<th>Specialization (if any)</th>
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<tbody>
<tr>
<td>Fred</td>
<td>1st</td>
<td>38 years</td>
<td>Special Education, Literacy</td>
</tr>
<tr>
<td>Liz</td>
<td>3rd</td>
<td>7 years</td>
<td>-</td>
</tr>
<tr>
<td>Jennifer</td>
<td>5th</td>
<td>13 years</td>
<td>Science</td>
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</tbody>
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*Table 2: Demographic information for the teacher participants*
The school’s demographics were representative of the state and district averages, and the school had recently been named a STEM school by the district, which meant it was expected to integrate STEM across all subjects, and provide students increased opportunities for engaging in STEM activities such as science fairs and university/industry partnerships. Even before this designation, the school employed an engineering coach who saw students periodically in a manner similar to music or gym classes, although grade-level teachers as a whole did not have any particular STEM training, nor were they required to cover engineering standards in their classrooms.

**Data Collection:** There were three sources of data for teachers’ ideas about engineering: pre- and post-interviews, observations during the professional development, and classroom observations while the teachers were enacting the lesson (see Figure 1). The professional development, interviews, and classroom lessons were videotaped and transcribed. In the classroom, the camera followed the teacher, focusing on his or her interactions with the students. Transcripts were coded with five common elements of the engineering design process—identifying the problem, planning, building, testing, and revising—in order to identify pertinent episodes which reflected teacher attention to student thinking throughout the EDP. Then, the teacher attentional skill framework (Table 1) was applied to each episode to characterize the teacher’s reaction to the students’ thinking.

**Interviews:** Prior to any training or classroom exercises, the teachers participated in pre-interviews that explored their understanding and beliefs of engineering and its role in the elementary classroom. After the lesson enactment, teachers participated in post-interviews that incorporated viewing two video clips of the classroom enactment of the lesson (including one clip that focused on the engineering design challenge portion) and a discussion of how their students met their objectives for the lesson. The purpose of this interview was to elicit teacher reflection upon their practice during that lesson, and their resultant thoughts about teaching engineering.

**Professional Development:** The three teachers engaged in an hour-long professional development session before the lesson which introduced a sample lesson plan, to which the teachers were free to make changes, some example student worksheets for recording the “Draw Yourself as an Engineer” and “Which Item is Engineered?” tasks, and planning space for the design challenge, and a rubric for the students to assess whether their build met the requirements. Teachers were also given access to the LEGO™ WeDo building sets in order to attempt to complete the challenge, of building a chair for a stuffed bear, that their students would be given.

**Lessons:** The lesson enacted by the three teacher participants in this study consisted of two parts, an introduction to engineering, and an engineering-design challenge. The introduction to
engineering section consisted of four activities to evaluate students’ existing ideas about what engineering is, and introduce a common definition of engineering design:

1) A “Draw Yourself as an Engineer” task, a variation of the “Draw an Engineer Test” designed to engage student ideas about what engineers do rather than an image of the stereotypical engineer;

2) A “Which Items are Engineered?” task, where students are presented 5 items and asked as a small group to identify which items are engineered (in every case, all of the items are engineered);

3) A discussion as a class about a common definition for engineering design; and

4) Brainstorming as a class a list of what an engineer would have to consider when designing a chair for their classroom.

Next, the lesson reviewed the kinds of pieces found in the LEGO™ WeDo building set. Students were then presented with the engineering design challenge, to “Build a Chair for Mr. Bear” which met six requirements:

1) Withstand being dropped from the student’s ankle (the “drop test”),

2) Be the correct size for Mr. Bear (a roughly 6-inch tall stuffed animal),

3) Have a sturdy back,

4) Keep Mr. Bear from falling out,

5) Raise Mr. Bear at least one inch off the ground, and

6) Use two different ways of connecting LEGO™ pieces together.

For the engineering design challenge portion of the lesson, students worked in pairs through elements of the engineering design process such as planning, building, testing, and as time allowed, revising the solution. At the end of the process, the lesson reviewed a sample seven-step EDP, synthesized from several sources: Ask, Imagine, Plan, Create, Test, Share, and Improve. The lesson materials given to the teachers during the professional development included a worksheet for “Draw Yourself as an Engineer” with space to draw and write, a worksheet for planning with space to draw and write, and a rubric with the six requirements for completing the “Build a Chair for Mr. Bear” challenge (See Appendix).

Enactment: Despite the teacher and classroom diversity, the enactment of the lesson in each classroom was very similar, with the teachers following the general lesson plan from the professional development, and assessing the same basic objectives of establishing the definition of engineering design and completing the design challenge. Teachers were given discretion as to when the lesson would be enacted, and whether the activities would be spread out over one lesson or several days; the average total time spent on the lesson was 2.5 hours.

Results: Elements of the Engineering Design Process

Through our analysis of the interviews and classroom data, several themes relating to elements of the EDP emerged. Across the three classrooms, with students of varying ages and teachers of varying experience, we found similarities and differences in how teachers interacted with student ideas and work, and in how the teachers seemed to understand the EDP itself. The teachers were initially not familiar or comfortable with definitions of engineering, and employed a more epistemologically complex definition of engineering while teaching than they expressed during the pre-interview, where the prevailing belief was that engineering was a “kind of science.” In the introductory interview, each of the teachers was asked about engineering design:
Interviewer: So, do you know what engineering design is?
Fred: I'll be honest.
Interviewer: Have you heard that term before?
Fred: No! [Laughs]

By the final interview, the same teacher had learned to recognize engineering design happening in his classroom, and had a very optimistic view of his students’ abilities.

Interviewer: How do you get across to them that the engineering process doesn’t always look like [the chart] though? Or is that something that first graders really don’t understand?
Fred: You know, they’re going to do it anyway. Whether the process is there or not. They’re going to ask the question, they’re going to sit and figure it out. They’re not going to follow this set of steps. But, they will on their own, in their own way, come up with the same type of process and go back and test it, retest, rebuild, retest. And I think they sort of do it on their own, probably not as scientific as this is, but they’ll do it.

Below we look at how teachers reflected on their students participating in five elements of that process during the design challenge, successes the teachers had in applying attentional skills to their students engaged in the work of an engineer, and instances where teachers require more support in guiding student practice, either in content knowledge or attentional skills.

**Identifying the problem:** The lesson provided (“Build a Chair for Mr. Bear”) presents students with a well-defined problem with six explicit requirements for the form, function, and materials of their chair. Teachers of the three grade-levels had to respond to different dynamics regarding the requirements throughout the lesson. In the first-grade classroom, Fred made rounds of the classroom repeatedly throughout the planning time, checking in on the pairs of students and whether they were attending to the six design requirements, but many students talked about additional requirements that they invented, such as adding cushions to their chairs to make the bear comfortable, or adding wheels:

Fred: What are you two girls talking about? What are you going to do for your chair?
Student 1: I’m going to have a wheel chair.
Fred: Add wheels to it, ok. And what else do you need to make your chair sturdy?
Student 1: We’re also going to make armrests like this.
Fred: Oh, I like that. It will have armrests. Ok, what else?
Student 2: A sturdy back.
Fred: A sturdy back, ok.
Student 1: And it will have four legs.
Fred: Four legs, I like that. Perfect. [Walks to next group.] Ok, listen, did you look at your chair and decide what you need on your chair?
Student 3: We have wheels.
Fred: You think it’s going to have wheels. Ok.
Student 4: I think armrests. It needs to have a little cup holder on the armrests. I think it
needs a place to put his feet.

Student 4: I think it needs to be a rocking chair.
Fred: You want it to rock, ok. You can try and see what happens. Ok, what else?
Student 3: I think it needs to be comfortable.
Fred: How is it going to be comfortable?
Student 4: It needs padding.
Fred: We’re only going to have bricks to work with. Can you put padding on there with just the bricks?
Students: No.
Student 4: We can pretend the bricks are padding.
Fred: We just need to make sure it’s really sturdy, ok?

In the post-interview, we asked for his reaction to the video clip of this conversation:

Interviewer: Were you surprised that kids were wanting to add wheels or cushions or colors?
Fred: I really wasn’t surprised with the wheels because every time we build something, they want to add wheels to it. The cushioning I was surprised, just because the product [LEGO™] they were working with was not soft, so that was kind of interesting. But I can see where the chairs that we looked at and the chairs that we have at home are all cushy, nicely padded chairs. But it didn’t seem to be an issue once they talked about how they would like to have a cushion, but it didn’t hold them up. It didn’t stop them from continuing to build their chair.
Interviewer: So, do you think that’s something that they can, with enough experience in the classroom, that they can learn by the end of the year, to sort of put aside the physical appearance and do that? So you don’t necessarily think it’s a developmental thing?
Fred: Well, yeah, I do think it’s developmental. Yeah, I mean, [Student 1] wouldn’t be able to get past that. Because she still wanted something, a red chair, it’s got to be red, and she would just stop at that point, unless you could talk her through it.

This episode represents a cognitive opportunity for the teacher, in that he asks the students to consider the six requirements given in the challenge, but he does not explicitly interfere with those requirements they had invented for themselves. This could have been taken further, incorporating his students’ invented requirements, if the teacher had recognized the potential to amend the class requirements to reflect those his students found more interesting. His attention took the form of noting the students’ invented requirements, but only interrogating the students to elicit all of their ideas and reasoning when their invented requirements are bound to complicate the challenge, as in the cushioning. The teacher has a methodical repertoire in his discussions with his students as he is circulating the classroom, so this is a reaction, or common strategy for asking and responding to his students’ thinking in a neutral manner. In the interview he recalls the episode easily and is able to articulate his strategy, allowing us to classify this as a conceptual choice in practice. This teacher, as a seasoned veteran with younger students, is able to be relatively impartial with his students’ ideas even when they are not what he expected, but does not wish to abandon the planned requirements for the chair in favor of his students’ suggestions.
Students in the third-grade classroom also added their own requirements, such as wanting to make their chair out of a single color of LEGO™ piece and adding wheels to the chair. Like the first-graders, building with requirements was a new concept for them, according to their teacher, who described previous building activities with LEGO™ bricks in the classroom as being much more open-ended and used to convey ideas instead of serving a functional purpose as a model. Like Fred, Liz did not try to dissuade her students from adding their own elements to the chair, and even rendered them assistance in accomplishing these requirements in their building:

Student 1: We're going to try to put him in the chair. We tried to make it two wheels, but I don't think that's going to work. Then we might do a footstool.

Liz: Well, here's my question. What if you did this the opposite way? Can the wheels be at the bottom [the axle was currently connected to the top of the seat instead of the bottom]? At the bottom, under the... [guides the student in moving the axle]. There's your wheel idea. Ah, good job. You guys are doing a great job.

This episode is also more of a cognitive opportunity, in that the teacher did not dissuade her students’ invented requirements as long as they were attending to the given requirements. Her reaction to students struggling in achieving these invented requirements is to note their difficulty and guide them toward a solution to their own problem, rather than steer them singly toward the given requirements. Liz is open to being responsive to her students’ invented requirements by tailoring the lesson to their interests, given further experience with engineering, and felt her students could develop to the point of creating their own set of requirements for a design challenge with proper practice working within given parameters in an activity such as this one, showing that her attention to her students’ thinking about requirements is conceptual.

Liz: I think that it would be fun to do a second time, of like, “This is what my requirements were, what are your requirements?” Or, after we’ve done one, do a completely different—don’t do a chair, do whatever—and make it that [the students] get to choose the requirements. Because I think if they had chosen the requirements, there would have been things like wheels, and then everybody’s would have looked more similar, which is what I was thinking [would happen].

Interviewer: One other thing is, if you were talking about some of the kids worrying about the color of the chair, or the appearance, if you said the chair had to be pretty, and that was a requirement, then you have to figure out how to judge pretty....

Liz: “I don’t like that.” Yeah, I can see that.

Interviewer: Which is nice about these requirements, they’re all discretely testable.

Liz: Yes or no. I mean, that could be a lesson in itself, of just saying, “What can be measured?” And we talk about that with goals a lot. They’ll say, “I want to get better at shooting a basketball.” Well, I don’t know how to tell [what better is]. So they get that some, but I do think you would have to have more time.

In the fifth-grade classroom, students had very little difficulty working exclusively on the six given requirements for the chair. It was only after groups started completing the challenge by meeting these requirements that Jennifer started adding additional “extra credit” goals for the students’ chairs to meet, an episode which is discussed in the revision section below. Fifth-grade students attended to the given requirements before adding their own, while the first and third-
grade students were interested in their own requirements before, or at least concurrent with, the given ones; if teachers give appropriate attention to the students’ own requirements, by treating them as a cognitive opportunity instead of a problem, perhaps the students could be coached in creating their own criteria for the building challenge. Liz, especially, was aware of this after enacting the lesson, and seemed interested in introducing the concept of testable requirements to her third-grade class in future challenges. Fred, in first grade, may be more wary of student-invented requirements, simply because following directions is an important skill developed in that grade. When teachers are encouraged to see deviations from the project’s requirements as opportunities for learning about testability or evidence that the requirements do not interest or challenge their students, as opposed to students not following directions, it opens avenues for deeper learning about engineering.

**Planning the solution:** All of the teachers emphasized the importance of planning a solution before building it, and all of the teachers required their students to draw and write about their plan, while allowing access to the LEGO® bricks they would be using. In the first-grade classroom, Fred had been trained as a literacy specialist, so drawing and then writing about those drawings was a familiar act for his students in the context of science lessons. For this reason, there were no major issues that required Fred to attend to student difficulties during the first-graders’ planning time. He described in the pre-interview how his first-graders were able to go into great detail during a lesson about fish by drawing their observations of their fish, then using the drawing as a basis for their writing, and then being encouraged to go back and fill in more details in turn on their drawing and writing. Fred, in later design challenges after this study, would also have students go back and draw and write again after they built, to plan for the revisions of their objects, or close their eyes and imagine the design before drawing it.

Liz had a very practical view of the time students spent planning, and how this time drawing and writing could be beneficial for her students. She accepted that some students needed to think with their hands by manipulating the materials, so that formal planning would only do them a certain amount of good. But she recognized that the process of planning together better facilitated her students sharing ideas as partners.

**Interviewer:** What did you think of the planning process? Did you think that it was important for your students? Was it important for them to meet the objective for them to have done the planning?

**Liz:** For some of them. I think some of the kids it really helped because it pushed them to really think, not just start building. But as, I know, it’s easier sometimes to build and then make it fit those requirements. The first time, once again, I feel like it’s good to think about it and plan it, but what I like is that [the planning stage] is a short time. It’s not like you have to go exactly by what you planned. I think that’s important for them to know. Like, I noticed I said that a few times, or somebody asked me, they said, “Do we have to do what we planned, if we make a change?” And I said, “No, absolutely change it. I just wanted you to think of this as how to start.”

**Interviewer:** And maybe they wouldn’t have asked that question if they hadn’t drawn something on paper to begin with. They would have just thought, “Oh, we have to fix it.”
Liz: Right. I think one student asked that question. Like, for him, it was really good to plan. Because it also makes them discuss and work together, rather than just one person taking over.

Her students’ cognitive problem was that they were unsure about the finality of their plans, but Liz was not unsure, and recalled this episode before it was even addressed in the interview, making it a very conceptual choice in practice:

Liz: Is that the bottom?
Student: Yeah, I added it. It’s not on the plan.
Liz: That’s ok, you can add it, you can change your plan. That was just an idea to get you started. But if you come up with another idea, do you think engineers just make a plan and stick to it and say, “That's it?”
Student: No.
Liz: No, because sometimes as you're looking you go, "Oh, I could do this."

Liz responds to the concerns of several groups besides this one, showing that it was important for her students to understand that the plan was a starting point, and to not feel pressured to stick with their original ideas. She noted their uncertainty without delving any deeper into her students’ ideas about planning, and addressed it with a clarification of her expectations of their plans. This episode is reflective of this teacher’s general philosophy in her classroom, in that she is more interested in the development of her students’ ideas than in a final product.

In the fifth-grade classroom, Jennifer said she made planning a priority objective for her students during the design challenge portion of the lesson. She also recognized that some students naturally wanted to plan before building, and that some did not, but she saw no benefit to the latter, and explicitly instructing her students not to start building during the planning time. In one instance, she takes an ELA student’s chair apart when she judges that he has started building instead of simply planning:

Jennifer: [Taking apart chair as other students look on.] Should we start building?
Student: Um, aww.
Jennifer: Ok. Here’s what we’re learning. Here’s what we’re doing. We know what we have [in the kit], you can test out how this is going to fit [trying two pieces together], test them out, and know what you’re going to draw. Not quite building yet, so we have a plan and we know our goals. So, ok? We’re planning [points to planning worksheet] and then building? Yes, ma’am?
Student: Yes.
Jennifer: [To the student’s partner] Help him.

Another group sees that student building his chair, and they decide they are done planning and can start their own. Jennifer takes their chair apart, as well. Jennifer has a non-conceptual recollection of the planning time, and never explicitly addresses taking the students’ chairs apart. She obviously addresses building before planning as a cognitive problem in the classroom, but on the contrary speaks as if it is sometimes acceptable during her interview:
Jennifer: I think that as far as what goes on in their head, I think that kids are different. So, some kids, and I had a kid like this, he probably never would have, even if I didn’t say it, the way his mind works, he never would have touched a single brick until his plan was [finished]. Only because that makes—order is just his joy. He is someone a process like that is ideal for, because, you know, he knows that, “I’ve got it. I know what I’m going to do. You’re handing me the next thing, and I’m doing it.” You know, so, for him, that’s a more natural way that he does everything. He doesn’t jump in, he sits and he thinks and he, you know, he kind of works through what he’s going to do before he jumps in to do it. And so many other kids are just, “Ah, you know, I’ll get it. I’ll figure it out as I go along.” And that’s ok, I don’t think there’s anything wrong with either thing. I think that kids at this level start to adapt.... I don’t know if I would ever say—I think there’s a possibility that the thinking is going on in both situations.

She mentions that her students place a different value to pencil-and-paper planning than she does, but she was only observed noting this idea, never asking her students to expand on why they felt the need to build before planning. Because it happened several times during the planning time, this episode can be labeled a response, albeit a possibly unconscious choice, to coerce her students into her ideal model of planning which might not be useful for this project or for their style of problem solving. Her insistence during the lesson that planning was achieved by having a sufficient drawing and words on their worksheet ignored the diversity of planning going on in her own classroom.

If teachers wish to emphasize planning, they need to consider what tools will actually be useful, if not essential, to their students for a particular design challenge. Or else, if the method of planning they chose for an activity is not working for some students, it is beneficial for them to treat this as a cognitive opportunity instead of a problem, and interrogate the students’ ideas with the hopes of coming up with a better planning method. Teachers can also benefit from noting a variety of behaviors which constitute planning and forethought in their students’ work when it happens at times other than the designated planning period.

**Building the solution:** It is difficult to talk strictly about the “building” element of the EDP within these classrooms, since the students were rarely engaged purely in just building. As was discussed in the previous section, many students continued to plan well past the “planning” time, and the predication of this continued planning was the micro-testing the students were engaged in as they built. In the first-grade classroom, as well as the fifth-grade, the teachers encountered the most problems during building when dealing with students solving the design challenge as partners instead of individually. All of the teachers agreed that working in groups was an important skill for students to develop, in and out of the context of engineering, and the availability of the materials necessitated that students work in pairs.

The fifth-grade students were understandably more comfortable working with a partner, but Jennifer still felt it was necessary to observe the groups carefully during the building time to make sure that one student was not dominating, or that another was not being passive or apathetic to the activity. This was a familiar, minor reaction to a common behavioral problem in this class.
However, in the first-grade classrooms, it took many pairs of students several reminders from Fred, both personally and as whole-class announcements, to realize that they were not just sharing materials, but that they were intended to build one chair between them. Fred named partner work as his main objective for this lesson, a very conceptual concern. He expressed that this was really the first time in the year he had required group work, and so it was not a familiar concept to them, making this less of a behavioral problem for his students, and more of a cognitive problem. Nearly twenty minutes into the building time, Fred realized one group was building two separate chairs, one for each student:

Fred: Now, are you working together, or are you doing your own chair and you’re doing your own chair? Because that’s not what we’re doing. We’re working together as a team.

Student 1: Well, first...

Fred: Well doesn’t work for me. You’re working together. With him? Are you working with her?

Student 2: This might work.

Fred: You might be able to put the two of them together somehow.

Student 1: I don’t know how to make this.

Student 2: [Looks wide-eyed at partner’s chair, starts taking hers apart] Let’s make it together.

While Fred anticipated problems with partner work, he did not specifically anticipate that students would persist in building separately, and it seemed to be a response more than something familiar to him. He noted when the students were not following his instructions to build one chair, and continued to visit their table until they understood his expectations. In general, however, the students needed the least guidance with the building element of the EDP, being so close to the natural play these students would engage in with the LEGO™ materials outside of engineering.

**Testing the solution:** In the lesson, students were given a rubric with the six requirements on it to use as an objective measure of whether a chair had met the design challenge. In the first and third grade classes, using the rubric required some degree of modeling. In the first-grade classroom, students did not understand the need for formal testing until one group finished their chair and the teacher modeled testing the chair following the rubric in front of the entire class. After that, Fred reported, the students understood better that building their chairs was working toward the goal of meeting the six requirements. In the third-grade classroom, students used the rubric to test their peers after switching chairs with another group, but things started to get disorganized as the lesson was running out of time and students were not sure of their instructions:

Student 1: [Trying to fix their chair that broke during testing.]

Liz: Excuse me. You’re not touching your chair right now. You’re not touching your chair.

Student 2: Does Mr. Bear fit in the chair?

Liz: [To group testing the chair] Use it from when it was together. Did it have enough
room for Mr. Bear to sit? Think about it when it was together, ok?

Student 2: Yes.

However, Liz indicated that her students could have used more modeling to ensure that the tests were objective and reproducible. She spent the testing portion of the class constantly addressing her students’ cognitive problems about the rubric and testing, responding to her students’ problems because there were many she could not have anticipated. Most of her time was spent noting the issues, since there was a lack of focus within her classroom, and time was running out for the lesson.

Interviewer: Where do you think they started to lose focus?
Liz: Testing

Interviewer: So, when they actually had to switch and do the [rubric]?
Liz: And I think because I hadn’t given a specific instruction, I tried to not—that was partly my fault. I think if we had said, “Ok, stop; let me model this for you.” Then, you know.

Interviewer: Do you think it was important that they switch the rubric and test each other’s? Or do you think their own testing that they were doing would have been sufficient?
Liz: Yes, because I feel like some of them, I don’t know, I was struggling with that, too. Because I felt like sometimes they dropped it, like when they were dropping it [for the drop test], if it was just things to look at that they could do that for any group. When it was actually dropping it and it broke, then they were kind of like, “Oh, it didn’t work.” And so I think they got that competition, and then sometimes they were like, “Well, yours broke, so I’m going to make your break.” And I’m like, no, we’re not going 7-inches [off the ground], we’re doing whatever it says on the rubric.

Interviewer: Ankle, yeah. So there was more competition.
Liz: Exactly, but I think that could have possibly been different if we had modeled that more, and said, “Ok, what are we going to do?”

This was a conceptual issue for Liz, and her suggestion of a discussion of making sure the tests were fair and objective would have turned this episode into a cognitive opportunity, and coincided well with Liz’s earlier suggestion of discussing testable requirements. In the fifth-grade classroom, the students were able to use the rubric to test another group’s chair with only behavioral difficulty, and Jennifer favored formal testing as a way to keep the students honest about whether their chair met the requirements.

Despite the need for modeling of formal testing for the younger students, all students engaged in some degree of testing naturally while they were building their chairs. The first-grade students traded the stuffed bear back and forth while building to make sure the base, back, and arms of the chair were sufficient to hold Mr. Bear. In this class, Fred pulled out a one-inch cube, a manipulative from math, to help his students measure whether they met the requirement that the chair be an inch off the ground. In the third-grade classroom, the students also utilized the stuffed bear to gauge their chair’s effectiveness during building, and pulled out their own rulers, unprompted, to measure the chair’s height. In the fifth-grade classroom, students even
conducted the drop test on their own chairs, before formal testing began. Any failures during this informal testing were addressed as the students modified their chairs during the building time they had left.

**Revising the solution:** All of the teachers complained about not having enough time to devote to this lesson, and they often cited revision as the element in the EDP which got shortchanged. However, as students were constantly testing and re-planning their chairs during the building time, they were also constantly revising their ideas. All of the teachers addressed the importance of revision and deviance from the original plan to their students at some point during the lesson. But without this reminder, students were never observed building a chair and then not testing it on their own before the formal testing period, or testing the chair and not addressing its failure by rebuilding it. Some students never stopped building, and without time limit on the lesson, would have gone on revising their chairs indefinitely. Jennifer was confronted with a cognitive opportunity of a group that had met the requirements and wanted to move on to their work for another subject, so she made up a new building goal students who had finished:

Jennifer: What you guys are going to do, you’ve got all yesses and you’ve met all the requirements?
Student 1: Yep.
Jennifer: So now you have a little bit of time while everyone else is trying to meet all the requirements to... kind of... make some luxury items. Make it be, really, “special.” Maybe add some accessories that might be cool for her to have on her chair.
Student 2: Like we could make a wall for her chair, so even if she tips over....
Student 1: We could make a couple [inaudible]....

She extended this new challenge to several other groups as they finished while other groups were still struggling to meet the requirements. This response to her students finishing early was not planned, so she noted her students’ lack of direction and called on their creative interest to find a way to engage them in continuing to revise by offering them a new, open-ended requirement. Jennifer was conceptually aware of her students’ pacing differences, and was willing to work within her plan to keep everyone engaged.

Jennifer: Any creative process like this, where you’re giving them sort of an open, you know, you’re giving them guidelines, but not giving them guidelines, you know, you never want to say, “Ok, stop.” Because kids are different, and some kids it might take them the first five minutes to go, “Oh, ok, yeah, and I’ve got it, let’s go.” And then that’s what’s lost, you know? If they had the extra five minutes, or if they kind of had at-your-own-pace kind of time, I guess that would be better.
Interviewer: It’s tough with the structure of school as it is.
Jennifer: Oh, it is.
Interviewer: Like, you’re trying to teach them that engineering is never finished, and keep iterating, and “Oh, but time’s up.”
Jennifer: Oh, exactly. That happens in everything. In writing it’s the same way. I’m always saying, “A good writer’s never finished. Now finish that!” ... I think a couple of those groups could have gone on for three days with adding accessories...
to their bear’s chair. But you do have to have some kind of parameters, just because of the physical day, you know what I mean? But also just because of the curriculum, and because of having to build on that and go on to other things.

The first-grade students also ran out of building time at the end of their lesson. In the week following the lesson, Fred encouraged his students to ask “what if” questions about the design challenge, and they came up with different requirements or similar new challenges of their own.

Fred: [Watching a video clip] Now these two are an interesting group because they are all over the place, and the fact that they actually stayed in their seat and focused for a long time shows that they were really interested.

Interviewer: Is that the group that finished first?

Fred: Yes, they were the ones.

Interviewer: They were the ones who did the test in front of the class.

Fred: The real excitement for me was the next day. When the kids had said, “Can we build again? Can we build?” One of them said, “Can we build a bed today?” And you know, so we just put the bricks out and said, “Go ahead and build.” The kids who had not been successful the day before wanted to go back and build the chair.... But it was kind of interesting to see the fact that the kids wanted to take it to the next level and come up with what would happen if we did this. They really enjoyed it, and we just put the bricks out on the table and let the kids go over there when they wanted to if they had their other work done. And as soon as the first group of kids went over there, all of the other kids started to go over there, started to build. And boy, they got their work done so fast, because they all wanted to be building again.

There is unfortunately no transcript from Fred’s follow-up building session with his class, but from his description, we can recognize that he approached his students’ requests to keep building instead of moving on in the curriculum as a cognitive opportunity, which he addressed with a common reaction of allowing open building time and encouraging what-if questions, as he often does in science and LEGO™ work, with interrogating his students’ ideas and letting them explore the materials and set their own, new goals.

Teachers expressed that they valued students engaging in revision and iteration when designing; however, upon implementation, they were frustrated by the amount of classroom time needed to allow students to build and rebuild their designs. They did appreciate the students’ enthusiasm for revision because it allowed the lesson to become differentiated. Within the span of one class period, one group of students might only complete one or two iterations of their design, while another group might revise until all the requirements are met, and then add requirements or creative elements in order to have a new goal to build toward. But rarely did a student sit idle, asking, “I’m finished, what should I do now?” and when they did, the teacher met it as a cognitive opportunity and offered a creative response, or a familiar “what if” reaction.
Discussion and Conclusion

At the end of the lesson, all of the teachers introduced a chart of the EDP, and they discussed the steps and how they related to the design challenge the students had just completed. The lesson had been designed with a time for planning, a time for building, a time for testing, and a time for revising, but these distinctions turned out to be superfluous. The real process of solving an engineering design challenge, with first graders or with professional engineers, is not a simple cycle, but a constant flitting from building to testing, from planning to building, from testing to revising; planning does not just happen with a pencil and paper before students start to build, and testing does not wait for rubrics and judging by other groups. With practice and professional development, teachers are made aware of how to recognize the elements of engineering design without the prescription that they happen in a specific order every time, these teachers reported that their students already seem to know this, as they make use of planning, testing, and revision instinctively while they build. This is the essence of using the attentional skill framework: when an experienced teacher discovers that their students’ are having difficulties with, or are eager to expand outside the boundaries of the planned lesson, attention-dependent knowledge helps her decide whether and how to deviate from this plan.

The teachers were given a lesson plan which provided time for each step in the engineering process, in turn, and belied the complex nature of engineering design. Because designing and building are open-ended, and because these teachers were not experienced with engaging their students in engineering, many situations arose where the students were not doing or thinking as the teachers anticipated they would. A detailed lesson plan might be sufficient for teachers engaged in a one-off lesson in order to give their students some exposure to engineering, but the goal of this project is to provide teachers with professional development such that they can integrate engineering into every subject in their classroom. This analysis has shown that using the attentional skills framework is useful in identifying the attention-dependent knowledge teachers use to respond to episodes contextual to each individual classroom and lesson.

Excepting one episode, teachers were shown making conceptual choices about how to respond to student thinking in their classrooms, and according to Ainley and Luntley’s framework, this is preferred, as it raises the possibility for reflection and revision of practice. A majority of the episodes featured teacher reactions, utilizing familiar strategies repeatedly. This either shows that the teachers have a repertoire of reactions that they have learned with their experiences in math, science, and LEGO™ building that are applicable to guiding their students through the EDP, or that they are unwilling to invent a new response to student thinking which would deviate from the lesson plan. In general, it would have been good to see more interrogating of student ideas and less noting, and this probably stems from unfamiliarity with the lesson, and therefore wanting to stick with the lesson plans and the objectives the teachers had identified for their students. The application of teachers treating their students’ ideas as cognitive opportunities versus problems, reflects teacher openness to allowing students to guide requirements through identifying the problem and revising the solution, but not wanting compromise on topics such as planning, building with a group, or engaging in methodical and reproducible testing. Teachers could open these steps up to being cognitive opportunities by addressing them as engineering habits of mind through a sustained engineering curriculum.
Based on the episodes analyzed here, teachers sometimes varied in how they responded to student thinking depending on the step in the process or on their objective for the lesson. For instance, they were more likely to treat issues in the Identifying the Problem and Revising the Solution stages as cognitive opportunities, and more likely to treat issues in the Planning, Building, and Testing the Solution stages as cognitive problems. With planning, building, and testing, particularly where the objective of the lesson was focused, such as working with partners or planning with pencil and paper, teachers followed the lesson plan more rigidly, approaching their students’ thinking as a cognitive problem, and were forced to generate new responses instead of familiar reactions to keep their students on track with the lesson plan. With regard to planning, we see some teachers identify that students can plan in different ways as long as they are productive, and others worry about locking students into a procedure. If the teachers are willing to respond to student ideas, students, even at young ages, could have more autonomy in setting requirements for their challenge and in determining what forms of planning are useful for their overall success. In these cases, if the teachers were not satisfied with their lesson, they had ideas for not only revising the lesson plan, but also the way they address their students’ difficulties during class.

This research has implications for developing training and support for teachers who are new to teaching engineering. Teachers come in with a myriad of attentional skills from science, and even writing, which help them deal with open-ended challenges such as this one. However, teachers will benefit from reflecting on their own practice teaching engineering with professionals and colleagues, and from learning to identify the elements of the EDP whenever they occur, not necessarily where they are scheduled to occur in the lesson plan. This study also contributes to the record of early elementary students engaged in engineering design, of which there are numerous more examples at the middle- and high-school level. Every class was successful with completing this engineering design challenge, although differentiation is obviously necessary for students at different ages and experience levels. Future research into the teachers’ understanding and beliefs about the EDP, pedagogical content knowledge and attentional skills, will be examined as these teachers engage in more extensive professional development with a larger cohort of teachers, and further curriculum development to create their own engineering lessons in the following school year. With regard to the attentional skill framework, future research could look for links between teacher attention and student outcomes.

References

9. Cejka, E. (2005). Inservice teachers' approaches to open-ended engineering design problems and the engineering design process. (Masters of Science), Tufts University, Medford, MA.
Appendix: Selected prompts from the provided lesson worksheets

Draw a picture of yourself doing engineering. Write a sentence or two about your picture. [Blank space for drawing and several lines provided for response.]

Which items are engineered?

<table>
<thead>
<tr>
<th>Item 1</th>
<th>Item 2</th>
<th>Item 3</th>
<th>Item 4</th>
<th>Item 5</th>
</tr>
</thead>
</table>

What is Engineering Design?
Engineering design is the process of creating solutions to human problems through creativity and the application of math, science, and technology.

Even the chairs at your desk were engineered. What qualities of your chair would an engineer have to think about while designing it? [Blank space provided for response.]

Challenge: Build a sturdy chair for Mr. Bear that will
- withstand the drop test
- be the correct size for Mr. Bear
- have a sturdy back high enough for Mr. Bear
- keep Mr. Bear from falling out
- raise Mr. Bear at least one inch off the ground
- use two different ways of connecting LEGO pieces together

Draw a picture of the chair you plan to build using your LEGO pieces. Write about how you will make it. [Blank space and several lines provided for response.]
### Chair for Mr. Bear Rubric

<table>
<thead>
<tr>
<th>Circle your rating below</th>
<th>Explain how you can turn the “No” into a “Yes”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Does the chair pass the drop test from the ankle?</strong></td>
<td>Yes   No</td>
</tr>
<tr>
<td><strong>Does the chair seat have enough room for Mr. Bear to sit?</strong></td>
<td>Yes   No</td>
</tr>
<tr>
<td><strong>Does the chair have a sturdy back that is high enough for Mr. Bear?</strong></td>
<td>Yes   No</td>
</tr>
<tr>
<td><strong>Does the chair keep Mr. Bear from falling out?</strong></td>
<td>Yes   No</td>
</tr>
<tr>
<td><strong>Does the chair raise Mr. Bear at least one inch off the ground?</strong></td>
<td>Yes   No</td>
</tr>
<tr>
<td><strong>Did you use at least two different ways of connecting the LEGO pieces together?</strong></td>
<td>Yes   No</td>
</tr>
</tbody>
</table>