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Elementary Preservice Teachers' Trajectories for Appropriating Engineering Design–Based Science Teaching

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Abstract
Learning to teach science using engineering design is a complex endeavor for elementary preservice teachers (PSTs). This entails helping PSTs understand students as sense makers and recognizing ways to notice, respond, and leverage their students' ideas throughout the design process. In this study, we follow a cohort of elementary PSTs through a 16-week method course including a related field experience in a local STEM intermediate school (grades 5–6) to better understand how they organize, plan for, and attempt to integrate engineering design–based science teaching. Data were gathered through interviews, lesson plans, reflective narratives, and classroom observations. Data were analyzed using open coding, document review, and cross case analysis. Results indicated that PSTs demonstrated three different ways they began to appropriate elements of engineering design–based science teaching, including adaptive approximations and compartmentalization of core practices as well as the replication of delivery pedagogies as practiced by school-based mentors. Recommendations for science teacher educators and instructors of science interested in integrating engineering design–based science teaching across contexts are provided.

Keywords Elementary preservice · Engineering design · Ambitious teaching

Introduction

Preservice science teachers (PSTs) face many challenges when learning how to teach effectively, such as developing professional knowledge about science content and practices (National Research Council [NRC], 2012), in addition to knowledge of how children learn and engage in science (Darling-Hammond & Bransford, 2007; NRC, 2008). Simultaneously, PSTs need to develop instructional strategies and approaches (Feiman-Nemser, 2001) that can foster productive learning opportunities for their students. These demands

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are compounded by PSTs' capacity to understand how to teach successfully to meet the goals of current reform-based initiatives, including new academic science standards (NGSS Lead States, 2013).

Since the national adoption of the *Next Generation Science Standards* in the USA (NGSS Lead States, 2013), inservice and preservice science teachers have been given the daunting task of learning to integrate three-dimensional science learning in their classroom practice. Three-dimensional learning engages students with using science and engineering ideas, practices, and crosscutting concepts to explore, examine, and explain how and why phenomena occur and to design solutions to problems (Krajcik, et al, 2014). This instructional approach is particularly challenging for PSTs who need to develop an understanding of the inter-relationship between science practices and engineering design for student learning.

Underpinning this reform is a new emphasis on engineering design that highlights the students' key role in defining and delimiting the problem and developing and optimizing design solutions (NGSS Lead States, 2013). This emphasis on student ownership of the design process necessitates PST notice students' ideas and practices to respond to their thinking, and promote analyses and reasoning about design decisions (Dalvi & Wendell, 2017; Levin et al., 2009). Yet, research indicates that novice teachers tend to focus more on content delivery and social conflicts within the classroom rather than student conceptions (Watkins et al., 2018).

Additionally, research has noted limitations of teachers' conceptual and procedural knowledge of engineering design, resulting in missed opportunities for supporting students' learning and understanding (Stein et al., 2002). Scholars have demonstrated that PSTs tend to replicate the practices of mentor teachers' practices without learning how to adapt or adjust their instruction to attend to their students' ideas (Anderson & Stillman, 2013; Braaten, 2019). Hence, science teacher educators are faced with the challenge of preparing PSTs not only to broaden their view of science education to include engineering, but also notice and support student engineering design thinking. The current study follows a cohort of elementary PSTs through their science methods course and related field experience in a STEM intermediate school (defined here as grades 5–6) to better understand how elementary PSTs organize, plan for, and attempt to leverage students' ideas and related science thinking using engineering design.

Purpose of the Study and Research Questions

Our study is guided by the following questions: (a) How do elementary PSTs *organize and plan for* engineering design–based science instruction as advocated in their elementary science methods courses? (b) Which engineering design–based science teaching practices do PSTs *attempt to appropriate* in their field experience? (c) To what extent does our analysis of PSTs' attempts inform us of PST's trajectories for learning to teach science through design? In this study, we take the perspective that PSTs' learning to teach science using engineering design is situated, social, and distributed; PSTs construct knowledge and appropriate practice together with others and through using authentic, practice-based discourse tools and teacher moves (Loughran, 2013; Wallace, 2003). These instructional activities are referred to as "high-leverage practices" (Ball and Forzani, 2009, p. 19) that represent core principles for effective science teaching and demonstrate the capacity engineering design has for facilitating student learning of science (Capobianco et al., 2020). Learning to engage with high-leverage practices thus takes shape as a trajectory that extends across time. These trajectories represent diverse routes into and around a set of high-leverage practices PSTs may take when attempting to implement engineering design–based science teaching. In this study, we seek to learn what kinds of trajectories PSTs develop based on their efforts to organize, plan for, and enact engineering design–based science teaching.

Theoretical Framework

Approximating practices for engineering design–based teaching requires PSTs engage in practices that are proximal to the practices of a profession (Grossman et al., 2009). In science education, this is referred to as *ambitious science teaching* (Windschitl et al., 2008), whereby "teachers help students of all backgrounds understand fundamental science ideas, participate in the practices of science, solve authentic problems together, and learn how to continue learning on their own" (p. 3, 2018). This kind of teaching requires instruction to be adaptive to students' needs and thinking while maintaining standards for participation and performance by all classroom students. In this manner, responsiveness to student thinking and reasoning is a precursor to ambitious science teaching.

In ambitious science teaching, students are recognized as sense-makers with powerful language and ideas worthy of attention (Braaten, 2019). Emphasis is placed on turns of talk that might otherwise go unnoticed within traditional classroom settings where responsive teaching is not practiced. Deeper understandings of compelling science phenomena, revised explanatory models backed by evidence, and student-generated ideas and questions are valued more highly than using technical vocabulary or recalling factual knowledge (Thompson et al., 2013; Windschitl et al., 2012).

At the heart of ambitious science teaching practices is the focus on noticing and responding to students' ideas and consequently, leveraging their ideas to facilitate and develop student learning. To clarify, teachers must notice and interpret when and how to employ high-leverage, discourse-based practices to maximize student engagement in and reasoning about engineering design (Chan et al., 2021; Johnson et al., 2017). In turn, this noticing and responding can influence what science and engineering experiences teachers provide to their students (Wendell et al., 2019) and what resulting artifacts are produced by students (Luna et al., 2018). As such, elementary inservice and preservice teachers need to learn to engage in responsive teaching (Barnhart & van Es, 2015); noticing, interpreting, and responding to students' science and engineering ideas and reasoning (Benedict-Chambers & Aram, 2017; Dalvi & Wendell, 2017; Watkins et al., 2018).

Ambitious Teaching and Engineering Design-Based Science Teaching

The tenets of ambitious science teaching align and translate well in the context of engineering design–based science instruction. Pedagogical features, such as responsiveness to students' thinking and reasoning, are key elements to engineering design–based science instruction. During engineering design–based science instruction, the teacher must adapt instruction to students' ideas, needs, and thinking as students progress from one design phase to the next. The teacher's discourse moves (e.g., guiding questions) are specialized, serving a specific purpose during each phase of the design process and furthermore, are used in combination with one another to elicit and build upon students' ideas, encourage students to make sense of their observations, emphasize key engineering ideas, and ultimately help students take up engineering discourse themselves. Table 1 provides an overview the types of questions teachers employ during different phases of the design process to foster student discourse.

In this present study, PSTs are introduced to, engage in, plan for, and test out these ambitious practices for engineering design–based science instruction in the elementary science methods course. In sum, we build on this framework by viewing how PSTs plan for and take up an ambitious practice (e.g., eliciting students' ideas, pressing students for evidence) and attempt to implement it during their earliest enactments of engineering design–based science teaching.

Context of the Study and Participants

The context of this study is an elementary science methods course located at a large, research-intensive university in the Midwest region of the USA. Undergraduate elementary education majors enroll in the course prior to their student teaching and eventual completion of the teacher preparation program. Participants in this study included 18 undergraduate students (PSTs): 13 White/Caucasian, 2 Hispanic, and 3 Middle Eastern female students.

The 16-week science method course includes lecture, lab, and field components. Through a series content-rich, standard-based engineering design tasks, PSTs engage in the engineering design process while simultaneously deconstructing their experiences as learners and prospective teachers of design. Emphasis is placed on immersing PSTs in standard-based design tasks while engaging in three-dimensional learning. For example, PSTs work in small design teams to plan, construct, and test a prototype of a compound machine designed to transport an injured large breed dog into and out of the back of a car (Capobianco et al., 2015). PSTs are introduced to simple and compound machines and the principles of work, force, and distance to become familiar with machines' mechanical advantages. PSTs then work through the design process to create and test models of their solutions. Simultaneously, PSTs are encouraged to identify and monitor the instructor's moves (e.g., types of questions asked, interactions with students, and organizational structure of the class). By doing so, PSTs decompose the instructor's practice and collectively recognize core practices associated with ambitious engineering design–based science teaching. At the end of each design experience, PSTs reflect on their design solutions, their engagement in the engineering design process, and the instructional strategies implemented by the instructor.

Additional course activities include PSTs developing and implementing one multi-day engineering design–based science lesson during a 4-week field experience at an urban intermediate school (grades 3–5). PSTs were instructed to adapt an existing design task (from the methods course or an approved database of classroom-tested design-based lessons for elementary school students) that would reflect (1) one core disciplinary idea, (2) one engineering practice, and (3) their classroom students' interests and prior knowledge of design. Following lesson implementation, PSTs prepare an electronic portfolio that includes the lesson plan, a reflective narrative, and samples of student work.

Methods

Data were collected via participant self-interviews, lesson plans, and reflective narratives. The purpose of the interviews was to capture how the PSTs articulated their ideas for organizing, planning for, and taking up ambitious engineering

Table 1 Guiding questions teachers use during different phases of the engineering design process to promote productive classroom discourse (Capobianco et al., 2018)

Design phase	Guiding questions	Features of ambitious engineering design–based science teaching
Problem scoping and information gathering	*What is the problem?* *What is the setting?* *Who is the user or client?* *What are the constraints?* *What do existing solutions look like?* *What other kinds of information do you need to know?*	Eliciting students' ideas with the goal of the design task in mind Eliciting students' ideas and prior knowledge about the context of the problem and big ideas
Solution formulation	*What are your ideas?* *What are others' ideas?* *What materials will you need?* *What will your team measure?* *What do you know about [big idea] that could help inform your design?*	
Solution production and performance	*How will your team create a prototype, model, or solution?* *To what extent does your solution match the team's original plan?* *How will you record results from testing?* *How could [big idea] explain your results?*	Eliciting and building upon students' ideas with the goal of helping students reason through their design solutions Inviting diverse solutions and supporting a range of understandings
Communication and documentation of results	*How did your model, prototype, or solution perform?* *What did you observe or notice about your design?* *How did the performance of your design compare to the performance of other design teams?* *Were there any patterns? What do these patterns tell us?* *What feedback did your team receive?* *How will you use this feedback to inform your model or solution?* *How could [big idea] explain your results?*	Encouraging students to make sense of their observations gleaned from constructing and testing Assisting students in collectively constructing evidence-based scientific explanations and models Encourage students to share and reflect on their solutions and performance results and their interpretations of these results
Optimization	*How will you improve your solution?* *What are the results from your retest?* *Which solution best addressed the problem?* *How could what you know about [big idea] explain what happened?*	

design–based science teaching practices. The purpose of the lesson plans was to document and chronicle their intended efforts. The purpose of the reflective narratives was to capture their interpretations of their attempts at attempting to enact ambitious practices. All procedures performed in this study, including obtaining informed consent, were in accordance with the ethical standards of and approved by the university's human research protection program. What follows is a description of each measure.

Self-Interviews

PSTs completed self-interviews prior to and following their participation in the methods course (n = 36 interviews). PSTs were given a series of questions and instructed to audio-record and upload their responses to a secured drive. Examples of questions included the following: What does engineering design mean to you? Why do you think it is important for teachers to teach science using engineering design? Why do you think elementary school children should learn to solve problems using engineering design? Self-interviews ranged from 20–45 min in length.

Lesson Plans

PSTs worked in pairs or individually to develop one multi-day engineering design–based science lesson that highlighted instructional objectives, science academic standards, learning outcomes, a standard-based design task, assessments, and modifications for differentiating instruction (see the Appendix Table 3). To meet the tenets of engineering design–based science teaching, PSTs were encouraged to outline, in detail, the questions (e.g., discourse moves), instructional strategies (e.g., notebooking), and classroom structure (e.g., whole class vs. small groups) they proposed to implement during each phase of the engineering design process.

In addition to the aforementioned features, PSTs were given an outline that started with a big idea or central science topic, an anchoring event and an essential question, and a sequence of learning activities. For example, one team examined force and interactions, specifically the difference between tension and compression forces. The lesson plan included a design challenge as an anchoring event in the form of the following essential question: Can you design a prototype of a lift to safely carry skiers up and down a hill? Emphasis was placed on encouraging students to identify and balance key forces applied to the lift. The lesson plan included questions that elicited students' ideas about forces, key instructional strategies that entailed making and recording observations, and organizing students for whole class discussion or small group work.

Reflective Narratives

PSTs prepared final electronic portfolios that included their lesson plan, evidence of student work, and a reflective narrative that depicted PSTs' attempts at enacting engineering design–based science instruction. PSTs' individual narratives described how they attempted to address students' needs and interests in science, align lesson objectives with three-dimensional learning, provide opportunities for students to develop and explain phenomena and design solutions, facilitate classroom/students discourse, and assess student learning. For this study, we focused on the different ways PSTs reflected on their efforts to notice and respond to students' ideas.

Classroom Observations

Classroom observations required simultaneously daily attendance in one or more science classrooms. This required multiple researchers throughout the course of PSTs' field experience. Hence, we identified a subset of PSTs (two pairs of PSTs and one individual

PST; total = 5 PSTs) from the larger group of PSTs who taught lessons independent of one another over the course of four to five class sessions ranging from 30 to 50 min per session (~ 11 h total). Multi-day classroom observations involved running logs of PSTs' moves including physical and verbal practices, discourse tools, and classroom organization as they occurred during the engineering design–based lesson (see Capobianco et al., 2018). For example, when researchers observed the PSTs instruct students to identify essential elements of the design problem, we noted this as PROB SCOPING, in teams as GROUP, and using their design notebooks as NB.

Data Analysis

Data were first organized by source: interviews, lesson plans, narratives, and observations. The second author transcribed the interviews, coded the transcripts, and prepared analytic memos. We used an existing validated coding scheme for features of ambitious engineering design–based science teaching to identify the different ways the PSTs organized their ideas for their instruction (see Capobianco et al., 2018). This coding scheme, aligned with the observation protocol in the current study, emphasizes teachers' (i) classroom organization (whole class, teams, individual), (ii) time spent per design phase, (iii) instructional activities (e.g., hands-on, discussion, notebooking), and (iv) level of student engagement.

The same coding scheme was used for analyzing the PSTs' reflective narratives. To determine how the PSTs *organized and planned for* responding to students' ideas, we reviewed the PSTs' lesson plans and mapped the contents to the features of ambitious engineering design–based science teaching (see Table 2). To clarify, the PSTs' lesson plans and our subsequent mapping of ambitious practices (see Table 2) were contingent on PSTs' interpretations of the lesson plan assignment and subsequent decisions they made when crafting their final lesson plans. We identified PSTs' questions, organizing ideas, and instructional activities and rated these features based on occurrence. For example, if a lesson plan listed questions like: "What do existing solutions look like? What are your ideas? What are others' ideas? How might the shape of your design influence its speed?," we noted these as *Eliciting students' ideas and prior knowledge about the context of the problem and big ideas*. If a lesson plan referenced opportunities for students to reflect on their design solutions (e.g., asking students how they would improve on their solutions or which solution best addressed the problem) and/or share their reflections with other students (e.g., organizing students into larger teams), we recorded that as *Encourage students to share and reflect on their solutions and performance results and their interpretations of these results*. It is important to note that although PSTs were instructed on the discourse tools of ambitious teaching and practiced the teacher moves of noticing and responding among their peers during design experiences in the methods course, they ultimately selected what to include in their lesson plans.

During the coding process, researchers met regularly to corroborate codes (Saldaña, 2015), and recurring codes were combined to form categories that then led to major trends (Bernard et al., 2016). Additional data analysis included document review of the reflective narratives of PSTs' teaching (Bowen, 2009). We then used observation and interview data to develop cases for select participant teams and conduct cross-case comparisons (Merriam, 1998). To ensure the trustworthiness of our data analysis, we employed triangulation using multiple data sets (Merriam, 2009).

Member checking allowed us to solicit feedback from the PSTs on our emerging findings (Merriam, 2009). We created a performance tool (see Findings) whereby we instructed

PSTs to rate their levels of performance with enacting engineering design–based instructional practices. This allowed us to rule out the possibility of misinterpreting the PSTs' attempts as well as the perspectives they had on learning to teach ambitiously. Pseudonyms were used to protect the anonymity of the participants.

Findings

Findings from our study are organized in the following manner. First, we present results from our analysis of PSTs' lesson plans to determine how PSTs *organized and planned* for engineering design–based science teaching. Second, we present results of our analysis of classroom observations that demonstrate how the PSTs *attempted to appropriate* engineering design–based science teaching practices in their field experience. Lastly, we discuss the PSTs' trajectories for engineering design–based science teaching.

Organizing and Planning for Ambitious Engineering Design–Based Science Instruction

The features most frequently cited were *eliciting students' ideas* and *situating students' ideas within the context of the problem*. This finding parallels results from previous studies. As Wendell (2014) noted, PSTs in practicum settings may focus on a narrow set of engineering design components and not be aware of factors regarding student thinking. Lesson plans also included attention to *encouraging students to share and reflect on their solutions and performance results and the interpretation of their results*.

Interview data supported one or more of the trends we observed in the lesson plans. Olive (Team 7) for example, described how she and her partner purposefully wanted to elicit students' ideas during problem scoping. In her post self-interview, she stated, "I know when we were planning our lesson, we wanted to be sure to include questions that would let us to find out what students might already know about the problem." Terry (Team 2) recalled the essential features of a design problem and leveraged these ideas in the following manner:

> When I think about planning for a design lesson, I always think about those essential questions I am going to ask once students read the design brief…what is the problem, who is the client, what are the constraints and how are you going to work within those constraints? (Terry, Post-interview)

Gina (Team 1) highlighted the significance of helping students analyze their results and their thinking about these results.

> An important feature of my lesson planning was to make sure I include questions I could ask to help students make sense of what they were doing…like after the design…how could they explain their results…like why the prototype worked or not. (Gina, Post-interview)

Attempting to Appropriate Ambitious Engineering Design–Based Science Teaching Practices

To determine how PSTs attempted to engage in ambitious practices, we analyzed the classroom observations of five PSTs (two pairs of two PSTs and one individual PST) and noted teacher moves that represented defined practices throughout the engineering design process. In this section, we present data from classroom observations and use interview data to support our preliminary claims about which core practices PSTs enacted.

Analysis of Olive and Sarabeth—Rescue Rover

The core practices exhibited by Olive and Sarabeth emphasized the elicitation of students' ideas throughout the design phases of problem scoping, planning, and communicating results. These teachers *strategically elicited and used students' ideas* through notebooking and whole class discussion. For example, during problem scoping, Olive and Sarabeth spent considerable time *asking students questions about their prior knowledge* about animal rescues. These included questions such as, "Have you ever seen an animal being rescued? How was the animal rescued? What kinds of devices were used?" These discourse moves allowed the teachers to contextualize the problem and "hook" students into the design task.

During problem scoping, Olive and Sarabeth asked questions like: "What do you think the problem is? Who needs our help? What are the constraints we need to consider?" Students extracted essential features from the brief to respond to these questions. Olive and Sarabeth *further elaborated on the importance of gathering students' ideas* about the position of the device, the distance it must travel down the paint pail, and its speed. For example, the following field notes from the classroom recorded dialogue between the PSTs and the students during problem scoping:

> Olive: What do you think the problem is? Who needs our help?
> S1: There's a puppy stuck in a sewer and we have to get it out safely.
> Sarabeth: What are the constraints we need to consider?
> S2: We don't have a lot of time.
> Olive: That's a good point…so how important is speed with our models? What do we need to know about speed?
> S2: Well, we would have to measure the distance from the top of the sewer to where the puppy is…
> Sarabeth: Anyone else…other ideas about speed? (*Students continue to share ideas).* How does the position or placement of your models affect its speed?
> S3: The model should be placed close or to the center of the puppy…you want to work fast….speed is important.
> Olive: What do you mean by this…perhaps we can draw what you are thinking… *(Teacher invites two students up to the white board to sketch their idea)*

Additionally, we observed the teachers ask questions such as "Does anyone else feel this way?" and "What do you mean by this…perhaps we can draw what you are thinking?" These discourse moves suggest that the teachers *elicited students' ideas, encouraged students to expand upon their ideas, distributed participation* by polling the class, and *pressed for explanations*.

Data from the PSTs' reflective narratives indicated that Olive and Sarabeth were purposeful about attending to their students' ideas:

> By asking students for their ideas, we quickly noticed how they thought about the problem and factors like mass and materials. We had one student draw his ideas and then we polled the class about what they thought. This led to a longer discussion about balanced/unbalanced forces (Olive).

Table 2 Alignment of design tasks with features of ambitious engineering design–based science teaching

Team	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
Features of ambitious engineering design–based science teaching *(*Capobianco et al., 2018*)*	**Chair lift**	**Reindeer habitat**	**Lifeguard chair**	**Candy bag**	**Prosthetic leg**	**Tower**	**Rescue rover**	**Ecosystem**	**Bottle racer**	**Crossing the river**	**Careful carrier**
Eliciting students' ideas with the goal of the design task in mind	x	x	x	x	x	x	x	x	x	x	x
Eliciting students' ideas and prior knowledge about the context of the problem and big ideas	x	x	x	x	x	x	x	x	x		x
Eliciting and building upon students' ideas with the goal of helping students reason through their design solutions				x		x	x				
Inviting diverse solutions and supporting a range of understandings						x	x				

Table 2 (continued)

Team	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
Encouraging students to make sense of their observations gleaned from constructing and testing	x		x	x	x	x	x		x	x	
Assisting students in collectively constructing evidence-based scientific explanations and models						x	x		x		
Encourage students to share and reflect on their solutions and performance results and their interpretations of these results	x	x	x	x	x	x	x	x			

> During team planning, we took time to find out what students were thinking. We walked around, talk with each team…it wasn't until we asked the class: 'We really what to hear your ideas about mass and force and how these factors might play a role in your designs' that led to this really neat sharing of ideas (Sarabeth).

The findings indicate that the PSTs profiled here stressed defining and delimiting the engineering problem with a focus on eliciting students' idea as well as developing possible solutions with a focus on student-centered idea generation.

Analysis of Ann and Shari—Chair Lift

Ann and Shari took a more prescriptive and conservative approach to their instruction. During problem scoping, the PSTs read the design brief to their students and asked questions like Olive and Sarabeth. However, Ann and Shari were observed *re-teaching* the essential elements of the original problem statement. For example, the following field notes are classroom recorded dialogue between the PSTs and the students during the first lesson on problem scoping:

Teachers are reading the design brief (narrative outlining the design problem) aloud to the children.

> Ann: What is the problem?
> S1: There's no way to get the skiers up the hill.
> Ann: Right…what are some constraints? [Pause].
> Shari: Remember constraints are limitations to the problem…so factors like time and materials are limiting factors in this problem, right?
> S2: Cost…we have a limit of $10.00.
> Shari: That is correct. So, remember from yesterday's reading on chair lifts we have think about those design features we want to include and the cost down.
> Ann: Okay, what is the next phase of the design process? Planning, right?

In this scenario, teachers *monitored* rather than *elicited* students' ideas and did not appear to probe or leverage students' thinking to enhance or extend class discussion. We speculate that Ann and Shari did not recognize the students' responses as an opportunity to explore their ideas further during problem scoping. Data from the PSTs' reflective narratives suggested the teachers were more focused on replicating their mentor teacher's practices rather than adapting their own practices in response to students' ideas.

> I thought our lesson went well and we met our objectives. Students were well behaved especially during the planning stages of their designs. The questions we asked allowed us to structure our lesson and provide some direction for the students (Ann, Reflective narrative).
> Using Mrs. B's method of guiding students through the design experience was very effective for us. I thought we were focused in our lesson and got through most of the design phases using the questions from our lesson plan (Shari, Reflective narrative).

This scenario reflects the PSTs' primary focus on getting through the lesson by requesting simple facts, categorizing students' responses as correct or incorrect, and/or responding to students by delivering content. Here, PSTs' abandon opportunities to move student thinking by not pressing students for their ideas and explanations. Consequently, emphasis is placed on mirroring the instructional practices of the PSTs' mentor teacher and structuring their lesson around closure-seeking questions and restricting student thinking.

Analysis of Teresa—Careful Carrier

Teresa's lesson objective was to encourage her students to identify the essential elements of a design problem including the criteria for success and constraints on materials, time, and cost. Her task required student teams to design a "prototype of a carrying device that would allow students with crutches to easily carry their own lunch tray" (Lesson Plan). She introduced her lesson by placing emphasis on *eliciting students' ideas* about the problem. During the first class session, students were given the design brief and then engaged in a whole-class discussion to unpack the details of the problem. At this time, Teresa asked questions such as "What is the problem?" "Who is our client?" "What are the desired features for your design solutions?," and "What are some limitations or restrictions to our design that we need to consider?" Interestingly, Teresa returned to these questions each class session while incorporating relatively few additional talk moves. Each session started with these discourse moves leaving less time for students to contribute or respond to other students' ideas. What follows are field notes from classroom dialogue between Teresa and her students during her third class session when students were testing their designs:

> Teresa: Okay class…remind me once more, what is the problem we are exploring?
> S1: We had to make something like a lunch tray for kids using crutches?
> Teresa: What were some of the desired features or criteria for your solution?
> S2: It has to be lightweight, attach to either the person or their crutches…
> S3: It has to be carried for ten feet and all the pieces of the tray are connected.
> Teresa: Did we have any constraints?
> S3: Will we able to test our solutions today?
> Teresa: Yes…but we want to review what our problem is about first…how about those constraints…does anyone remember?
> S2: We use only the materials we were given and…
> S1: When we test it today we can't be holding the carrier ourselves…there has to be an attachment.
> Teresa: Why do you think it is important we create something like this carrier?
> S2: Because we want to help those kids who have a hard time with getting their lunches
> Teresa: Right…and who is our end user?
> S3: We already said this…kids with crutches…

Rather than diversifying her discourse practices throughout her instruction, Teresa employed the same talk moves for each class session. These included asking display questions to elicit an anticipated correct answer. We refer to this particular series of discourse moves during engineering design–based science instruction as *anchoring* (Capobianco et al., 2018). Here, Teresa uses these talk moves as an instructional anchor to ground and re-orient her students in the problem. By returning to the original design problem during each class session, Teresa strategically attempts to meet her original instructional objective but overlooks opportunities to leverage student thinking, noticing but not drawing upon students' reasoning.

Mapping PSTs' Approximations of Ambitious Practices

To better characterize the PSTs' attempts at implementing features of ambitious engineering design–based science teaching, we developed a tool that displayed the PSTs' performance along a continuum for the different dimensions associated with the engineering practices (see Fig. 1). The far left column represents engineering practices as presented by the *Next Generation Science Standards* (NGSS Lead States, 2013). The next column represents the features of ambitious teaching that align with the engineering practices (Capobianco et al., 2018). The remaining columns represent the different levels of sophistication of these practices. The upper levels of each feature (right end of the continuum) are consistent with advanced practice as defined in expert–novice studies (e.g., Windschitl et al., 2012). The lower level for each feature (left end of the continuum) represents surface-level dimensions of the respective practice. The upper level (right end of the continuum) characterizes teacher moves that press students to share ideas, reason about links between observable and unobservable features of the problem and engage in dialogue about evidence and/or revised solutions. From a developmental perspective, moving from the lower to the upper levels of all the features requires increasing sensitivity to and awareness of student thinking.

Since PSTs' field experience was relatively short-lived (implementation of one lesson within three to four sessions with students), we considered the use of this tool as a creative opportunity to have PSTs reflect on their development of practice before continuing with their student teaching in the next academic semester. Olive and Sarabeth indicated their performance at a relatively high level of sophistication including discrete talk moves that involved referencing and leveraging students' ideas to propel their instruction forward. They also noted how they could improve on ways to help students connect their design results with essential features of the design problem. Ann and Shari, on the other hand, admittedly recognized their talk moves ranging from conventional to more sophisticated as they progressed through different engineering practices. Teresa reinforced our observations of her favoring less sophisticated talk moves. Many of the PSTs considered these first attempts as "stepping-stones" to eventually approximating the practices on the right side of the continuum.

Discussion

PSTs in this study demonstrated promising intentions to organize and plan for engineering design–based science teaching, indicating their capacity to plan for ambitious engineering design–based science teaching that placed emphases on one or more core practices. Three trajectories of practice emerged from PSTs implementation: (a) *adaptive approximations for ambitious design–based science teaching practices*, (b) *compartmentalizing a practice within a design phase*, and (c) *using delivery pedagogies as a guise for ambitious design–based science teaching*.

The first pathway — adaptive approximations —suggests that several PSTs were able to appropriate, organize, and enact one or more responsive design-based teaching practices (Olive and Sarabeth), while others foreclosed on such opportunities (Ann, Shari, and Teresa). The second pathway was identified by discrete episodes when PSTs enacted one practice: isolated from other elements of the practice. Thompson et al.

(2013) refer to this as compartmentalizing an ambitious practice. Teresa, for example, emphasized eliciting students' ideas in isolation from other practices through her enactment.

The last pathway — using delivery pedagogies — highlighted an 'observe-and-mimic' approach utilized by PSTs. This approach is governed by cultural norms and routines of a recitation style of instruction exercised by the mentor teacher and often adopted by PSTs (Sfard & Prusak, 2005). Instead of making space for new teaching and learning experiences by capitalizing on opportunities to explore students' thinking, Ann and Shari abandoned ambitious teaching practices and replicated these normative patterns, failing to notice and respond to students' ideas. Such rote replication minimizes productive adaptions of what was learned from their university methods course and opportunities to reorganize and retool their teaching practices (Braaten, 2019).

We can assert that PSTs who participated in this study engaged in different types of discourses and practices, leading to different developmental trajectories of practice. By the end of their field experience, PSTs planned for and enacted a suite of practices that resulted in discursively oriented classrooms, yet the depth of their students' talk about design varied. Much of this variation can be attributed to the significant amount of time required to appropriate and learn from high leverage practices (Thompson et al., 2013). The science methods course the PSTs participated in was their first experience with enacting engineering design and ambitious teaching practices. This was compounded by a field experience situated in a school setting where mentor teachers asserted clear institutional agendas for covering content and keeping pace with colleagues.

Understanding each trajectory problematizes developmental theories that refer to a single trajectory of professional growth for preservice and novice teachers (Bullough & Baughman, 1997; Hogan et al., 2003). Unlike these explanations, our trajectories begin to account for variation in developing practice by recognizing the multiple forms of discourses prospective teachers engage in and the influence of context, pedagogical tools, and time in the field.

It is important to consider the limitations of our study. This study is limited by two factors including our sample size and data sources. Lesson plans and observations do not paint a complete picture of teachers' adoption of ambitious science teaching. This is compounded by the small subset of cases we were able to identify within the larger methods class of eighteen PSTs. Unlike similar work related to teacher noticing and responding (e.g., Barnhart & van Es, 2015), we did not videotape PSTs' lessons. While videotaping and analysis would have been informative and advantageous, the public schools in this context do not permit videotaping due to issues of confidentiality, anonymity, and protection of minors. Supplementing our research efforts was the lack of research personnel to observe each PST teach simultaneously across several days. We maximized our efforts by identifying those PSTs who taught independently of one another and adjusted our observation schedule accordingly.

Conclusions and Implications

The aim of this study was to examine how PSTs organize, plan for, and attempt to appropriate engineering design–based science teaching practices as a result of participating in an elementary science methods course that advocated for such practices.

Findings indicated that PSTs placed emphasis on one or more core practices when developing lesson plans and enacting engineering design–based science teaching. Our classroom observations of PSTs' instructional practices demonstrated that PSTs enacted diverse trajectories into and around the set of instructional practices offered to them in the course. Consequently, we were able to develop a tool to characterize the types and variation in PSTs' trajectories. Our approximation of engineering design–based practices tool may motivate other researchers and science teacher educators to examine how their PSTs and their respective programs address the enactment of reform-based science instruction. This tool could provide a source of reflection before, during, and after PSTs engage in their field experiences. This tool could also be used by inservice teachers who host, mentor, and observe PSTs in their classrooms and wish to provide formative and summative feedback to PSTs on their instruction. This tool may also be utilized by science teacher educators when modeling and reflecting on best practices in their methods courses. Lastly, this tool could be employed by science instructors who wish to examine their efforts with learning to implement high leverage practices in core science courses for PSTs. By embedding and modeling high leverage practices for engineering design–based science teaching, course instructors can help PSTs recognize, navigate, and actualize these practices themselves with less difficulty and more confidence and precision. Continuity across learning-to-teach contexts, such as undergraduate science content and methods courses, is imperative for productive science teacher development. Equally important is cooperative input from mentor teachers, district coaches, and school administrators. Aligning visions and practices of ambitious engineering design–based science teaching across these contexts may likely benefit new teachers and their capacity to be innovative in the ways they foster productive learning opportunities for their students.

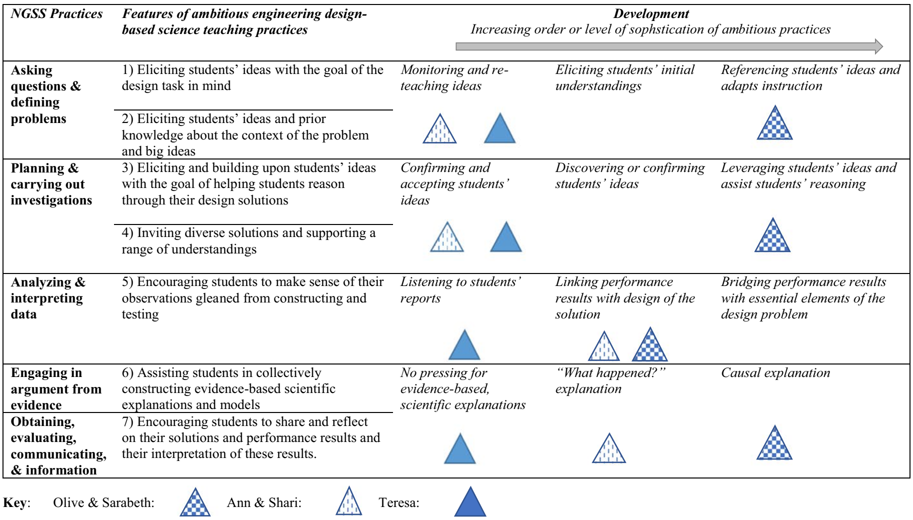

Fig. 1 Results of PSTs' implementation of ambitious engineering design–based science teaching practices ($n = 5$ PSTs)

Appendix

Table 3 List of PSTs' lesson plan objectives and related science standards

Task	Grade	Design objective	Disciplinary core idea	Science and engineering practice	Crosscutting concept
Chair lift	5	Design a prototype of a lift to carry skiers up and down a hill	Motion and stability: forces and interactions	Asking questions and defining problems	Cause and effect
Reindeer habitat	5	Create a reindeer exhibit for a local zoo	Matter and energy in organisms and ecosystems	Developing and using models	Scale, proportion, and quantity
Lifeguard chair	5	Design a prototype of a lifeguard chair for a local pool	Motion and stability: forces and interactions	Developing and using models	Structure and function
Candy bag	5	Create a candy bag that holds the greatest mass and volume	Motion and stability: forces and interactions	Asking questions and defining problems	Cause and effect
Prosthetic leg	5	Design a prototype of a prosthetic limb for a young soccer player	Motion and stability: forces and interactions	Developing and using models	Structure and function
Tower	5	Create a display tower for the town library	Motion and stability: forces and interactions	Developing and using models	Structure and function
Rescue rover	6	Design a device that will help rescue a puppy from a well	Motion and stability: forces and interactions	Constructing explanations (for science) and designing solutions (for engineering)	Structure and function
Ecosystem	5	Design a zoo enclosure for a coyote	Matter and energy in organisms and ecosystems	Developing and using models	Energy and matter: Flows, cycles, and conservation
Bottle racer	6	Design, construct, and test a prototype of a car that uses an alternative energy source to power the vehicle	Matter and its interactions	Planning and carrying out investigations	Cause and effect
Crossing the river	5	Devise a way for local farmers can transport their goods across the county river	Motion and stability: forces and interactions	Developing and using models	Structure and function
Careful carrier	5	Design a carrying device that would allow students with crutches to easily carry their own lunch trays	Motion and stability: forces and interactions	Asking questions and defining problems	Systems and system models

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Availability of Data and Material All data is password protected and stored in the Purdue University Research Repository (PURR). Access to the PURR can be made upon request to the corresponding author.

Code Availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

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