Preparing Secondary Pre-Service Science Teachers for Engineering Design Integrated Science Teaching

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A Dissertation

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Doctor of Philosophy

By

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Abstract

This dissertation includes three studies focusing on pre-service science teachers' (PSTs) self-efficacy for engineering teaching and implementation of engineering design integrated science (EDIS) instruction. These investigations collectively highlight the efforts to enhance PSTs’ understanding and self-efficacy in implementing engineering design in science teaching, following interventions embedded in science methods courses and field experiences. The first manuscript is a review of existing literature on engineering design teacher preparation. The findings provide important context on how best to improve interventions seeking to prepare PSTs for teaching science using engineering design. The findings of the other two manuscripts reveal that such educational interventions significantly boost PSTs’ capacity to innovate and adapt engineering principles in teaching, evidencing growth in their ability to integrate engineering with science education effectively. This growth is supported by increased self-efficacy post-intervention, indicating sustained confidence in teaching engineering design. The studies advocate for more comprehensive preparation in EDIS, suggesting a positive trajectory towards improved science education that incorporates engineering design, thereby fostering a holistic understanding and application of STEM concepts among future educators.

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APPROVAL OF THE DISSERTATION

This dissertation, *Preparing Secondary Pre-Service Science Teachers for Engineering Design Integrated Science Teaching*, has been approved by the Graduate Faculty of the School of Education and Human Development in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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Dedication

To my mother, I will forever miss you.

Thanks for always loving me even when I did not reciprocate.

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I would like to express my heartfelt gratitude to my advisor, Dr. Frackson Mumba, whose unwavering support and guidance has been instrumental in making this dissertation and my scholarly journey possible. From the very start, Dr. Mumba challenged me to strive for excellence and provided me with the necessary resources to achieve my goals. He also created a nurturing environment that allowed me to develop and grow as a researcher. I will always be grateful for the invaluable platform and space he provided me with to pursue my academic aspirations.

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Preparing Secondary Pre-Service Science Teachers for Engineering Design Integrated Science Teaching: Linking Document

The main objective of this dissertation is to investigate and add to the existing research on preparing pre-service teachers (PSTs) in engineering design integrated science (EDIS) teaching. I chose this area of study for two reasons: First, it merges my two research interests: Engineering design integration into science teacher education and science teacher professional knowledge. Second, engineering design in science teacher preparation is new, and everyone is learning how to integrate it into teacher education appropriately. As such, there is much to uncover about preparing PSTs in engineering design and how to integrate it into science classrooms. Therefore, my research can potentially contribute to a field that is new and needs more exploration.

This research is split into three parts: a literature review and two empirical studies. I am the main author of the three manuscripts, handling parts of the design, execution, and analyses. However, I will use existing data that was collected in two NSF research projects that were designed to prepare PSTs for EDIS teaching. The participant PSTs learned about engineering design and how to plan and teach EDIS lessons. They also taught EDIS units in schools during student teaching. Each manuscript aims to explore how PSTs are prepared to integrate engineering design into science teaching. Each manuscript informs the others in a progression, from a literature review (Manuscript 1) to a quantitative study (Manuscript 2) to a qualitative study (Manuscript 3). These manuscripts are linked conceptually by their focus on science teacher preparation in EDIS teaching. The framework for manuscript 1 is adapted from Rutt et al.’s (2021) framework for language and literacy integration in science instruction. The adapted framework (see Figure 1 in manuscript 1) guided the analysis of the empirical studies on engineering integration in science teacher programs. The two empirical studies are further linked by their frameworks, which revolve around the experiential and affective nature of PSTs' learning. The framework for Manuscript 2 was researcher-designed around the desired effects of self-efficacy after instruction on EDIS, and that of Manuscript 3 was based on McLellan's (1996) situated learning theory. These frameworks guided the structure and analysis of the empirical studies and the interventions. In aggregate, the three manuscripts of this dissertation seek to summarize and add to the research on preparing PSTs in EDIS teaching. I provide a brief overview of each manuscript below.

Manuscript 1: Preparation of Pre-Service Teachers in Engineering Design Integrated Science Teaching: A Review

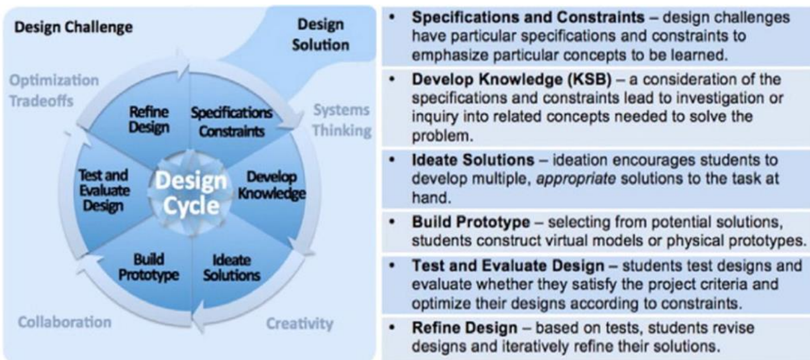
The first manuscript in a three-manuscript dissertation is a review of existing literature on the preparation of PSTs in engineering design integrated science teaching. The study aimed to review the current research on teacher education interventions focused on preparing PSTs to teach science using engineering design. Specifically, we want to investigate in what ways EDIS intervention programs are addressing structural and content components, which we call tasks for learning that are key to PSTs' preparation, as outlined in the framework (see Figure 1 in manuscript 1). The following research questions guided the study: (a) What are the variations in the structure of interventions designed to prepare PSTs for EDIS instruction, and to what extent do they support outcomes for PSTs' learning and implementation of EDIS instruction? (b) What are the variations in the tasks for learning outlined in interventions designed to prepare PSTs for EDIS instruction, and to what extent do they support outcomes of PSTs' learning and implementation of EDIS instruction?

The review focused on studies conducted between 2013 and 2023 in pre-service teacher preparation programs in the United States and written in English. A total of 22 studies were identified and evaluated based on structural and task-oriented components that are essential for teacher preparation, as outlined in the framework adapted for the review. Results show that the structural components and intervention tasks were prevalent to varying degrees in the reviewed studies. Some tasks of learning outlined in the framework were understudied or underrepresented in the studies reviewed. In general, the findings of this study offer an understanding of the emerging field and could potentially guide the development of future interventions for engineering design integration in science teacher education programs. While I collaborated closely with Dr. Mumba on this manuscript, I am the primary author and am currently finalizing it for revision before submission to the *Journal of Research in Science Teaching* by December 1, 2023. In essence, this research delves into the nuances of engineering design in science teacher preparation programs, providing valuable insights that could inform future efforts in the field.

Manuscript 2: Developing Secondary Pre-Service Science Teachers' Self-Efficacy for Teaching Engineering

The second manuscript of the three-manuscript dissertation is the first of two empirical studies. Informed by findings from Manuscript 1, both empirical studies were based on PSTs' participation in the intervention on EDIS teaching in a science teaching methods course. The studies were done to add to research on preparing PSTs to teach science using engineering design. In these studies, the EDIS instruction in a science methods course was operationalized by the informed engineering design model (Chiu et al., 2013) (Figure 1). This model was introduced to PSTs at the outset and directed the tasks during the intervention. As depicted in Figure 1, the core wheel of the model encompasses these components: design challenge, defining specifications/ constraints, cultivating knowledge, brainstorming solutions, constructing prototypes, and assessing, evaluating, and enhancing designs. Supplementary aspects of engineering design reside outside the wheel—systems thinking, creativity, collaboration, and optimization tradeoffs.

Figure 1
Engineering Design Instructional Model (Chiu et al., 2013)



In Manuscript 2, I investigated the change in 40 secondary science PSTs' self-efficacy for teaching engineering following their participation in EDIS intervention in teacher education. Specifically, my research questions were: (1) To what extent does participation in the instruction on EDIS teaching in a science methods course and teaching EDIS units in schools impact secondary science PSTs' self-efficacy for teaching engineering? (2) Are PSTs able to sustain their self-efficacy beyond the EDIS instruction? (3) To what extent does science PSTs' self-efficacy for teaching engineering change throughout the EDIS instruction when controlling for gender and teaching subject areas?

The data utilized in this study came from the *Teaching Engineering Self-efficacy Scale* (TESS; Yoon et al., 2014) questionnaire that was completed by the PSTs before and after the EDIS instruction, as well as after implementing EDIS units in schools during student teaching. The findings indicate that the PSTs' self-efficacy for teaching engineering design significantly increased after participating in the EDIS instruction in a science methods course, and this self-efficacy was maintained during their EDIS unit implementation in schools. Additionally, a linear growth model analysis confirmed the positive coefficients for time, indicating that the EDIS instruction and implementation (coded as time in the data) had a significant influence on PSTs' self-efficacy for teaching engineering. Manuscript 2 was initially reviewed during my preliminary exam, and since then, the results and discussion have been enhanced. Following the review by the preliminary exam committee, I have revised and submitted this manuscript to the *Journal of Science Teacher Education*, and it is currently in review.

Manuscript 3: Pre-Service Teachers' Implementation of Engineering Design Integrated Science Instruction

Manuscript 3 is the second of the two empirical studies. Building on the prior manuscript focusing on PSTs' self-efficacy, this study reports on how PSTs who participated in the EDIS teaching intervention driven by situated learning theoretical framework (McLellan, 1996) learned and used EDIS instruction in schools during their student teaching experiences. This exploration is important given the increasing emphasis on integrating engineering design in K-12 science education, as set forth by the Next Generation Science Standards (NGSS; NGSS Lead States, 2013). The study provides a structured instructional model to educate secondary science PSTs about engineering design and how to integrate it into science lessons. Additionally, this investigation is set apart by its grounding within a specific theoretical learning framework – the situated learning theory. The emphasis on this framework addresses a gap in the literature, as many existing engineering interventions in teacher education programs lack such a theoretical foundation (e.g., Conley et al., 2000). Through this research, insights will be garnered into how these PSTs planned, executed, and reflected on their instructional practices in real-world classroom settings. Thus, Manuscript 3 seeks to answer the following research questions:

1. After completing an engineering design integrated science intervention, how did pre-service teachers plan and implement engineering design integrated science lessons in schools during student teaching?
2. To what extent did pre-service science teachers innovate upon what they learned in the science methods course about engineering design to support their EDIS instruction during student teaching experiences?

I used existing data that was collected in two NSF-funded research projects in 2017-2018. The EDIS intervention is the same one described in manuscript 2. Data sources include PSTs' EDIS units, classroom observations, and interviews. The data collected assessed the PSTs’ ability to integrate engineering design into science instruction based on what they learned during the EDIS intervention. All EDIS units PSTs planned and taught in schools were collected. Classroom observations were conducted using the Engineering Designed Integrated Science Classroom Observation Protocol (EDIS-COP), which has 30 items and several subscales. The EDIS lessons taught by PSTs were videotaped. The EDISCOP protocol was developed by the PI of the two NSF projects in which the data was collected. Semi-structured interviews were also held with PSTs after they taught their EDIS units in schools. Reflections were collected through the reflection assignment in which PSTs were asked to reflect on their EDIS teaching in schools. For data analysis, three phases were applied: categorization of the EDIS units into application, adaptation, and innovation; quality assessment of the EDIS units using an evaluation rubric; and analysis of lesson observations, and interviews for evidence of instruction impact, including the identification of emerging and main themes from participant responses. After completing the manuscript will be submitted to *Science Education* in April 2024 for review and possible publication.

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Manuscript 1

Preparation of Pre-Service Teachers in Engineering Design Integrated Science Teaching: A Review

Abstract

US science education reforms advocate teaching science using the engineering design process, but many science teachers lack preparation in engineering. To address this, science teacher education programs have started preparing pre-service teachers (PSTs) in engineering design integrated science (EDIS) teaching. However, little is known about the structure of interventions and tasks for learning used to prepare PSTs in EDIS teaching. We examined research studies on preparing PSTs in EDIS teaching for variations in their structures, tasks for learning, and outcomes, using a framework that has components for preparing PSTs to teach science using engineering design. Results show most interventions were integrated into science teaching method courses and field experiences, with longer interventions leading to better outcomes. Most studies reported PSTs' increased understanding of the engineering design process, EDIS instructional planning, and self-efficacy for teaching engineering. However, some tasks for learning, such as providing tools to evaluate EDIS instruction and its influence on student learning, supporting PSTs in examining their beliefs about EDIS teaching, and understanding how to teach engineering design in diverse classrooms, were understudied. The findings have implications for science teacher preparation, science and engineering teaching and learning, and future research.

Keywords: Engineering, pre-service teacher, science, learning, teaching

In the United States, science education reforms (National Research Council [NRC], 2012; NGSS Lead States, 2013) emphasize teaching science using engineering design process (EDP). These science education reforms are aimed at fostering the connection between engineering and science to enhance student learning of science and engineering content knowledge and skills that include analytical thinking, imaginative thinking, and problem-solving (National Academy of Engineering [NAE] & NRC, 2009). These skills are essential in preparing students for careers in science and engineering and nurturing a deeper appreciation for the significance of the two fields in the modern technological world (NAE, 2014; Rogers et al., 2014). Additionally, research shows that engaging students in science and engineering can help them to understand how scientific knowledge is developed, the nature of engineering, the work of engineers and scientists, and similarities and differences between the two fields (Authors, 2017; Moore et al., 2014). For this to happen, science teachers should have an understanding of engineering design and how to integrate it into science teaching (Mesutoglu & Baran, 2020; Deniz et al.,2020).

However, research shows that many science teachers feel unprepared to teach engineering design integrated science (EDIS) lessons to their students because they have little or no coursework in engineering (Banilower et al., 2018; Kim et al., 2019). Therefore, the call for engineering design integration into science teaching will only be realized if science teachers are prepared in EDIS instruction. Both science and engineering education communities have identified this gap in science teacher preparation and have called for the integration of engineering design into teacher education programs (Maiorca & Mohr-Schroeder, 2020; Love & Hughes, 2022). In response to this problem, several science teacher education programs have started preparing pre-service teachers (PSTs) in engineering design and how to integrate it into science teaching. However, little is known about the nature of interventions that are being used in science teacher education programs to prepare PSTs in EDIS teaching. We acknowledge that the integration of engineering into science teacher education is new, and research on this topic is still emerging. However, we believe that the extant studies on this topic can provide key insights into informing future teacher preparation programs and research on EDIS instruction in teacher education. Therefore, the purpose of this paper was to review the extant research studies on preparing PSTs in EDIS teaching. Specifically, we wanted to investigate in what ways the structure of and tasks for learning evident in extant interventions contribute to PST learning outcomes and implementation of EDIS instruction, and to consider in what ways those findings can inform future teacher preparation and research. This review sought to answer the following research questions:

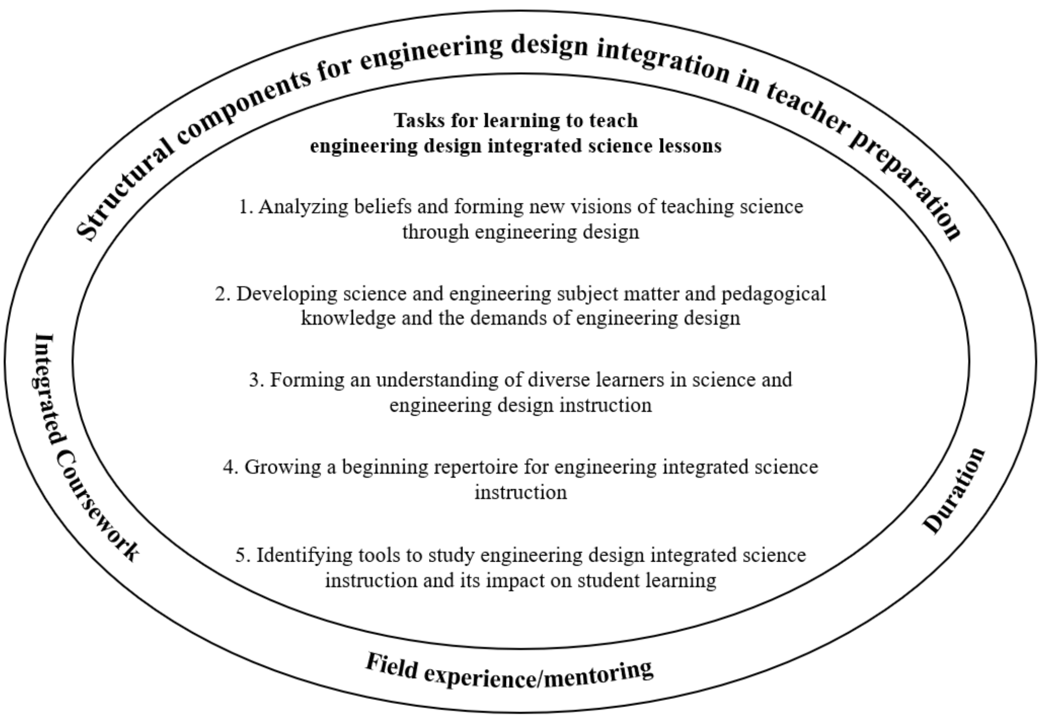
1. What are the variations in the structure and tasks for learning outlined in interventions designed to prepare PSTs for EDIS instruction?
2. To what extent do the variations in the structure and tasks for learning outlined in the interventions support PSTs learning outcomes and implementation of EDIS instruction?

Theoretical Framework

Research studies have addressed PSTs' integration of engineering design in science teaching, employing frameworks that either concentrate on latent variables like self-efficacy (e.g., Antink-Meyer et al., 2023; Menon et al., 2023; Yesilyurt et al., 2021) or focus on subject matter knowledge such as engineering or other subjects (e.g., Hammack & Vo, 2022; Pleasants et al., 2019). Most of these frameworks have focused particularly on the tasks that PSTs should be able to accomplish but fail to address important structural components of teacher preparation programs, such as duration, the role of field experiences, and coursework integration. Therefore, the framework proposed by Rutt et al. (2021) for preparation of PSTs in language and literacy integrated science instruction in linguistically diverse classrooms was adapted to guide the analysis of studies on preservice teachers' preparation in EDIS teaching (see Figure 1). The framework builds on scholarship in teacher preparation generally (e.g., Feiman-Nemser, 2001) and science teacher education (e.g., Barak, 2017), and takes into consideration some key structural components of teacher preparation that may support PSTs' development as EDIS teachers. Additionally, the efficacy of the modified framework is derived from its emphasis on essential structural components for the preparation of science teachers in integrating engineering design into science teaching.

Figure 1

Framework for preparing PSTs to teach in EDIS classrooms (Adapted from Rutt et al. (2021))



As shown in Figure 1, the outer circle delineates key structural components for science teacher preparation programs. The inner circle shows the tasks PSTs must master to effectively integrate engineering design into science teaching. Each circle encapsulates a different facet of teacher preparation—program structure versus course-specific content/tasks— with the structural components outlined in the outer circle being essential to achieving the tasks set out in the inner circle. For example, integrated coursework, a structural component, facilitates PSTs' comprehension of engineering design and how to integrate it into science lessons and understanding of science and engineering practices. Similarly, another structural element, field experience and mentoring, offers an environment for PSTs to develop repertoires of EDIS instructional practices and identify tools to evaluate instruction and its influence on student learning. Hence, the tasks for teaching are contextually situated within broader structural components of the teacher preparation program. The individual components and elements of the framework are described next.

Structural Components for Engineering Design Integration in Teacher Preparation

The outer circle of the framework has three structural components essential for preparing PSTs in integrating engineering design into science teaching: integrated coursework, duration, and field experiences with mentoring. Although other structural components (not in this framework) may influence PSTs' adoption of targeted instructional practices, these specific elements are integral to teacher preparation and professional development. (e.g., Desimone, 2009; Garet et al., 2001; Hammerness et al., 2005). Each component is explained in the next sections.

Duration. Research shows that effective teacher preparation relies on sufficient professional development (PD) duration, including the hours spent and the span over which it occurs, as it often yields better outcomes when sustained (Garet et al., 2001). For PSTs, extended interventions necessitate cohesion across various teacher education program components, such as semester courses and field experiences. This cohesion, vital for general and EDIS teaching preparation, enables PSTs to engage with and revisit key concepts throughout their preparation (Desimone, 2009). Program cohesion can be supported by integrated coursework, field experiences, and mentoring, which we will explain next.

Integrated Coursework. The NGSS indicates that integrating engineering and science enhances students' critical thinking, problem-solving abilities, and ability to apply scientific knowledge in real-world scenarios (NGSS Lead States, 2013). Therefore, preparing PSTs to seamlessly integrate engineering design into science teaching is key to realizing NGSS objectives. The proposed framework highlights the importance of integrated coursework where teaching methods courses emphasize the integration of engineering and science in teacher education programs. This should lead to PSTs developing an intuition for creating these connections when developing their EDIS lessons (Maiorca & Mohr-Schroeder, 2020). Engineering design should be taught within the context of science teaching methods courses rather than as a stand-alone course (e.g., Kaya et al., 2019; Mumba et al., 2023; Yesilyurt et al., 2021). We also believe engineering should be integrated into science content courses required in teacher preparation. Such an approach allows PSTs to make the natural connections between engineering design and science and how to integrate the two disciplines. Further, by teaching engineering design as a part of science teaching methods and science content courses, the engineering design process (EDP) is positioned as a central component of what it means to teach science through engineering (e.g., Nesmith & Cooper, 2021), aligning with the three dimensions in the NGSS and providing a focus on engineering and science knowledge and skills that are beneficial for all students.

Field Experience and Mentoring. Field, or practicum experiences, is an essential component of teacher preparation programs, as it contributes significantly to programmatic cohesion. Additionally, field experiences have positive impact on PSTs' learning outcomes and their subsequent teaching practices (McDonnough & Matkins, 2010). For example, studies show that field experiences are essential to PSTs' abilities to incorporate novel teaching methods into their practice, such as culturally responsive teaching and inclusion for special education students (Kent & Giles, 2016; Pence & Macgillivray, 2008). This evidence suggests two essential considerations for teacher preparation programs. First, programs should allow PSTs to practice integrating engineering design into science instruction with students (Capobianco et al., 2022) during field experiences. Second, PSTs need to participate in science instruction within K-12 classrooms where mentor teachers can reinforce the EDIS instruction. Given the profound influence of field experiences and interactions with mentor teachers on PSTs' beliefs and instructional practices (Clarke et al., 2014), this approach can mitigate the discord that arises when PSTs are expected to implement reform-based practices in classrooms where traditional instruction prevails (Cochran-Smith et al., 2015; Thompson et al., 2013).

Tasks for Learning to Teach Engineering Design Integrated Science Lessons

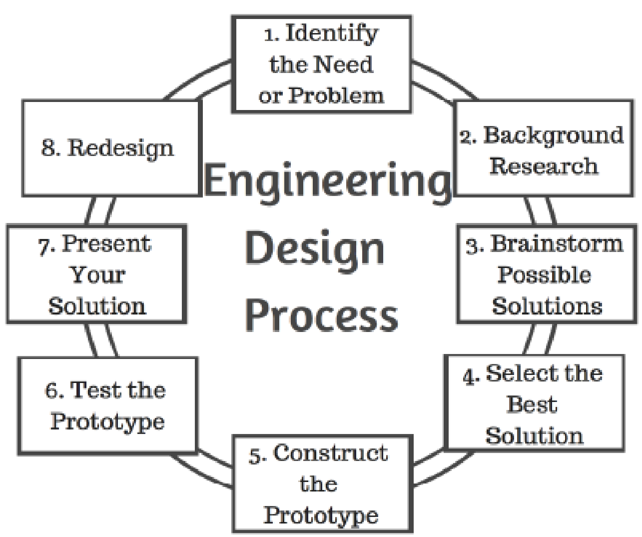
Though the key structural components of teacher preparation programs described above are essential, the tasks used to prepare PSTs bear equivalent significance (Hill, 2006). Leveraging the framework proposed by Rutt et al. (2021), we have adapted the five tasks to align with PSTs preparation in EDIS instruction. This process culminated in a modified version of Rutt et al.'s tasks, adapted explicitly for preparing PSTs to teach science through engineering design. The tasks are described next.

Analyzing Beliefs and Forming New Visions of Teaching Science Through Engineering Design. For many PSTs, the teacher preparation program is their first experience with EDIS teaching (Kilty & Burrows, 2021). Therefore, understanding PSTs' beliefs, conceptions, or perceptions and how they influence their science instruction is fundamental to any changes in their instructional methods (Kotuľáková, 2019). Regarding EDIS instruction, this analysis extends to PSTs' beliefs about the role of engineering design integration in science classrooms, especially because PSTs may hold strong beliefs about engineering design and the role it should play in science classrooms (Capobianco et al., 2022; Kilty & Burrows, 2021). This can have far-reaching effects on PSTs' classroom enactment of engineering design. For example, PSTs with a teacher-centered belief about science teaching might struggle with teaching science using the engineering design process (EDP). The requirement that students actively participate in the EDP activities might cause significant dissonance for such PSTs, limiting their ability to implement EDIS instruction in science classrooms. It is important, then, that teacher preparation programs provide PSTs with opportunities to critically examine their beliefs about effective instructional practices to determine how those practices align with ambitious EDIS instruction accessible to all students.

Developing Science and Engineering Subject Matter and Pedagogical Knowledge and the Demands of Engineering Design. For PSTs to successfully incorporate engineering design into their science teaching, they must possess subject matter knowledge in both science and engineering, including their interconnectedness, as noted by Nixon et al. (2019). This requires a thorough understanding of the distinct characteristics of each field, as well as how they intersect - for example, how engineering can be applied to scientific inquiry and how scientific methods can be utilized to address engineering challenges. In addition to possessing knowledge of science subjects, it is equally important for PSTs to know how to teach these subjects using engineering design problems. The significance of pedagogical content knowledge in science teaching has been acknowledged since Shulman's work in 1986, and the importance of a similar construct in EDIS teaching is gaining attention in current literature (Love & Hughes, 2022).

Part of the required engineering knowledge is the appreciation of the iterative nature of the engineering design process. It is essential that PSTs understand and appreciate the cyclical nature of engineering design, testing, and redesigning of engineering prototypes, as represented in Figure 2 below. Hence, to better equip PSTs, teacher education programs must prepare teachers to recognize and appreciate the EDP within science classrooms and develop the skills necessary to help students identify and utilize these features of engineering design while engaging in science (Love & Hughes, 2022). We also believe it is important for engineering design courses to be offered as part of the required content and teaching methods courses in science teacher education programs. These courses can further bridge the gap between where PSTs are in their engineering content knowledge (Banilower et al., 2018) and where they need to be to successfully address the NGSS in their science teaching in schools.

Figure 2
Engineering Design Process Model (Authors)



Forming an Understanding of Diverse Learners in Science and Engineering Design Instruction. For students to develop an interest in and appreciation for the practicality of science in their daily lives, they need to understand how science instruction connects with their own experiences and interests (National Research Council [NRC], 2012). PSTs must also learn how to gain insight into their students, families, and communities and use this knowledge to inform their teaching methods (Lane et al., 2019). This is especially important when working with minority students who may feel disconnected from engineering cultures. Similarly, in science classrooms that incorporate engineering design, it is essential for teachers to understand their students' previous experiences with science, inside and outside the classrooms, and to learn about their inquiry skills and how their daily experiences can inspire innovative engineering design solutions (Mejia et al., 2014). They should also be prepared to teach EDIS lessons in classrooms that have special education students, second language learners, and minority students.

Growing a Beginning Repertoire for Engineering Integrated Science Instruction. Teacher education programs should enhance PSTs' familiarization with different instructional models, curricular resources, and assessment approaches for EDIS instruction. These models, resources, and approaches should be aimed at improved instructional planning and classroom implementation of EDIS instruction in science classrooms. The ultimate goal is to help PSTs determine the most effective way to use these resources and methods in their teaching (Feiman-Nemser, 2001). In EDIS teaching, teachers should be well-versed in student-centered instructional methods and how to develop and adjust curricular resources to provide engineering-related support that enhances students' participation in challenging science activities (Maiorca & Mohr-Schroeder, 2020). PSTs need opportunities to participate in, discuss, and observe rigorous EDIS instruction. This will help them gain valuable experience in scaffolding their EDIS teaching while ensuring the rigor of science learning appropriate for their students' age (Kent & Giles, 2016).

Identifying Tools to Study Engineering Design Integrated Science Instruction and Its Impact on Student Learning. According to Feiman-Nemser (2001), PSTs need the ability to examine diverse aspects of student work, know a wide variety of curricular materials, and have access to tools that allow them to be receptive to student feedback in their instruction. PSTs should also be engaged in reflective teaching (Shandomo, 2010). These qualities are critical to PSTs being able to study their teaching, and subsequently improve their instructional practices. This also includes analyzing the instructional decisions made by other practitioners. For teachers in EDIS classrooms, these skills are essential to reflect on and critically evaluate instruction, curricular decisions, and student outcomes while keeping engineering design challenges in mind. Therefore, teacher preparation programs should provide PSTs with opportunities to develop such skills, tools, and instruments for informed instructional decision-making in their future classrooms. The framework's inner and outer circles represent the practical, theoretical, and logistical components of PST preparation for EDIS teaching. We used this framework to guide our literature search, analysis, and organization of results.

Methods

A multistep literature review was conducted to answer the research questions. This literature review required studies to be peer-reviewed, empirical, conducted, and published between 2013 and 2023. This ten-year period was chosen because the NGSS standards were published in 2013 (NGSS Lead States, 2013). We believe that it was after the publication of the NGSS that most teacher education programs started preparing teachers in EDIS teaching. Therefore, it is assumed that studies on engineering design intervention in teacher education published during this ten-year period were aligned with the current framework for K-12 science education (NRC, 2012) and NGSS (NGSS Lead States, 2013). Additionally, only peer-reviewed studies conducted in the United States and written in English were reviewed, as national education policies can influence practice and research in different countries (Villegas et al., 2018). In the US, the current framework for K-12 science education (NRC, 2012) and the NGSS (NGSS Lead States, 2013) require science teachers to teach science using engineering design process.

The search for relevant articles was done in the following educational research databases: EBSCO, ERIC, Academic Search Complete, Education Full Text, PSYC Info, Education Research Complete, and Psychology and Behavioral Science Collection. Key terms/phrases, descriptors, and/or all text fields were used to search. The primary terms used in the search were 'preservice teacher education,' secondary search terms were 'science', and specific disciplines ('chemistry', 'physics', and 'biology'), and tertiary terms were 'engineering design.' and 'engineering'. Keyword searches were prioritized, but all text fields were the secondary option if there were no results from the keyword searches. To ensure as many relevant articles were included, a secondary search was conducted through specific peer reviewed science and engineering education journals where we used the search phrase 'preservice teacher preparation engineering design integration' to identify relevant articles. The journals included in this secondary search were the International Journal of Science Education, Journal of Science Teacher Education, Science Education, Journal of Research in Science Teaching, Research in Science Education, International Journal of STEM Education, Journal of Science Education and Technology, Journal of Engineering Education, School Science and Mathematics, International Journal of Science and Mathematics Education, and the Journal of College Science Teaching.

From the research databases, 130 articles were obtained, and 411 results from the journal searches for a total of 541 articles. After eliminating article duplications from different sources, using the Zotero reference manager (Version 6.0.26), the number of articles came down to 472.

To ensure that the articles met our criteria described above, the titles and abstracts of each article were reviewed according to the guidelines outlined in the first paragraph of this section using the Zotero reference manager (Version 6.0.26). First, the article title was assessed to determine if it met our selection criteria. If the title did not provide enough information, the abstract was read and assessed for inclusion. If inclusion could not be confirmed, we skimmed the article's methods section for confirmation of inclusion. Ultimately, 22 studies were identified and included in the review. Each study was thoroughly evaluated to identify the framework's structural components and tasks for learning (see Figure 1) and outcomes. The presence and/or absence of each component or task for learning and how they were implemented in the studies were reported using a table (Table 1). The table also includes a column for study outcomes, both positive and negative, as well as the reasons suggested by the researchers for the reported outcomes. The results are organized by framework components, as presented below.

Results

The studies reviewed provided insight into the integration of engineering design in science teacher education programs. The variations observed were in the kinds of learning opportunities available, engineering design activities, engineering design instruction models, instructional planning, and teaching opportunities. As shown in Table 1 below, most studies focused on elementary PSTs. Only five of the 22 engineering integration interventions reviewed were for secondary PSTs (Carpenter et al., 2019; French & Burrows, 2018; Kim et al., 2019; Mumba et al., 2023; Ryu et al., 2019). Twelve studies were qualitative (Capobianco et al., 2022;

Capobianco & Radloff, 2022; Carpenter et al., 2019; Estapa & Tank, 2017; French & Burrows, 2018; Kim et al., 2019; Maiorca & Mohr-Schroeder, 2020; Menon & Azam, 2021; Pleasants et al., 2019; Ryu et al., 2019; Tank et al., 2020; Wendell, 2014), six studies were mixed methods (Antink-Meyer et al., 2023; Hammack & Vo, 2022; Menon et al., 2023; Pleasants et al., 2020; Webb & LoFaro, 2020; Yesilyurt et al., 2021), and four studies were quantitative (Kaya et al., 2019; Mumba et al., 2023; Nesmith & Cooper, 2021; Perkins Coppola, 2019).

Among the studies that used qualitative analytical methods, the most common method adopted by nine studies was open coding analysis (Antink-Meyer et al., 2023; Capobianco et al., 2022; Capobianco & Radloff, 2022; Hammack & Vo, 2022; Kim et al., 2019; Pleasants et al., 2020; Ryu et al., 2019; Tank et al., 2020; Webb & LoFaro, 2020). Seven studies were content or document analysis (Capobianco et al., 2022; Estapa & Tank, 2017; French & Burrows, 2018; Maiorca & Mohr-Schroeder, 2020; Menon et al., 2023; Menon & Azam, 2021; Pleasants et al., 2019). Two studies took a case study analytical approach (Menon & Azam, 2021; Tank et al., 2020). Thematic analysis was the approach adopted by Yesilyurt et al. (2021) and Carpenter et al. (2019). The last two studies used discourse analysis (Wendell, 2014) and constant comparative analysis (Kim et al., 2019). For studies that used quantitative analytical methods, six of them used either a parametric or non-parametric form of paired samples test, i.e., paired sample t-tests or the Wilcoxon signed rank test (Kaya et al., 2019; Menon et al., 2023; Nesmith & Cooper, 2021; Perkins Coppola, 2019; Webb & LoFaro, 2020; Yesilyurt et al., 2021). One study used the Mann-Whitney U test (Hammack & Vo, 2022), two studies adopted the Chi-Squared test of association (Antink-Meyer et al., 2023; Pleasants et al., 2020) and Mumba et al. (2023) utilized descriptive statistics for their analysis.

Upon a thorough review of each study using the framework (see Figure 1), the findings revealed that almost all studies had integrated coursework. This means that in most of the analyzed studies, the engineering design intervention was conducted within science teaching methods courses. Additionally, most interventions included field experiences. Analysis of these field experiences indicates a variance in the role of these experiences in their objectives and outcomes. The duration of the intervention also varied, with some studies reporting one week to one year, while others described one or more semesters. All studies focused on developing science and engineering subject matter and pedagogical knowledge, with all but one also addressing beginning repertoires for EDIS instruction. However, most studies reviewed did not include three of the five tasks listed in the framework: examining PSTs' beliefs about engineering, understanding diverse learners, and identifying tools for studying EDIS instruction and student learning. It is essential to acknowledge that the literature used to develop our framework and the framework itself were created as guidance for teacher preparation programs. In this review, most of the interventions analyzed might only highlight one aspect of a more extensive teacher preparation program. Thus, our focus is on the reported outcomes within the context of these studies, recognizing that individual engineering design interventions may not cover all framework components when viewed as parts of more extensive teacher education programs. We present the results below to gain insight into how different programs prepared PSTs for engineering design integration in science classrooms.

Structural Components for Engineering Design Integration in Teacher Preparation

Duration. The duration for engineering design interventions in teacher education programs described in the reviewed articles varied from a week to a year (see Table 1). In most studies reviewed, the intervention lasted a semester and varied from 13 to 16 weeks (Antink-

Meyer et al., 2023; Capobianco et al., 2022; Capobianco & Radloff, 2022; Hammack & Vo, 2022; Menon et al., 2023; Nesmith & Cooper, 2021; Perkins Coppola, 2019; Pleasants et al., 2019, 2020; Tank et al., 2020; Webb & LoFaro, 2020; Yesilyurt et al., 2021). The rest were enacted over five weeks (Carpenter et al., 2019), two weeks (Kaya et al., 2019), and one week (Estapa & Tank, 2017; Maiorca & Mohr-Schroeder, 2020). Only one study reported one year intervention (Menon & Azam, 2021). Five studies did not explicitly state the duration of their intervention (French & Burrows, 2018; Kim et al., 2019; Mumba et al., 2023; Ryu et al., 2019; Wendell, 2014), but it was deduced that it could have taken place in a semester. Most of the reviewed studies did not directly link their results to the duration of the engineering intervention. Few studies linked the outcomes to the duration of the interventions. For example, Webb and LoFaro (2020) said time played a role in the development of self-efficacy for teaching engineering among PSTs. They also noted that the PSTs participated in a 15-week course on engineering content knowledge and pedagogy, which was longer than the courses studied in other authored studies (e.g., Kaya et al., 2019; Maiorca & Mohr-Schroeder, 2020). The longer duration of the course positively impacted the PSTs' self-efficacy for teaching engineering practices, with larger effect sizes than in previously published studies by other authors (e.g., Dailey et al., 2018; Perkins Coppola, 2019).

Capobianco et al. (2022) also highlighted the benefits of longer-duration engineering design instruction in their discussion. They indicated that as the PSTs engaged in various engineering design-based experiences throughout the course, they began to shift their focus from learners of engineering design to teachers of engineering design-based science instruction. The findings of their study suggest that the participatory, performative, and experiential nature of engineering design facilitated the PSTs' development of engineering pedagogical content knowledge (PCK) as learners during their teacher education. Similarly, Menon and Azam (2021) found that new and fresh experiences gained during teacher preparation courses can have lasting effects on the development of teacher identity. The authors emphasized the significance of their study's year-long duration, which allowed them to observe the evolving identities of PSTs at multiple intervals. This extended timeframe revealed that the true understanding and impact of the science methods course on teacher identity, both immediate and long-term, became more pronounced a year after the course concluded. This was evident in the practical application of their learning in real classroom settings and the gradual realization of their teaching inclinations and challenges.

Comparing two studies with similar objectives but different durations can complicate the conclusions we can draw about the impact of duration on the outcomes of engineering design intervention in PST learning. For example, Kaya et al. (2019) and Perkins Coppola (2019) conducted studies to evaluate the improvements in PSTs' self-efficacy for teaching engineering resulting from participating in specifically designed integrated engineering design coursework. Both studies used the paired student t-test for data analysis, with Kaya et al. utilizing the Engineering Teaching Efficacy Belief Instrument (ETEBI) and Perkins Coppola using the Teaching Engineering Self-Efficacy Scale (TESS). While Kaya et al. conducted their engineering coursework over a period of two weeks, Perkins Coppola's course lasted for 14 weeks. Despite the difference in duration, both studies found similar results, with significant improvements in self-efficacy constructs, except for outcome expectancy. In Perkins Coppola's study, the p-value for their outcome expectancy construct was below the 0.05 threshold, but they classified it as not significant due to the small effect size (less than 0.2). Similarly, Nesmith and Cooper (2021) noted that although their results were generally positive, the PSTs' experiences were limited to a short period of engineering design intervention. As a result, they suggested follow-up sessions in future versions. Wendell (2014) also indicated that the PSTs' experience was deficient in specific aspects of engineering design, such as information gathering, solution modelling, and evaluation of solutions. They indicated that the PSTs could have benefited from more time and opportunities to engage in these facets of engineering design. The authors further stated that increasing the duration or providing more open-ended and longer-term engineering design problems might help PSTs develop a more comprehensive approach to engineering design in science classrooms.

Despite the similarity between these two studies, holistically, the length of engineering design integration instruction plays an important role in shaping the science and engineering teaching development of PSTs. This implies that science teacher preparation programs that integrate engineering instruction into their science teaching methods courses should ensure that they allocate sufficient time for PSTs to engage in engineering activities and develop EDIS lessons, which will facilitate optimal mastery and preparedness for classroom enactment. For instance, interventions should include follow-up sessions while PSTs implement EDIS instruction in science classrooms. This approach would enable the PSTs to gain further insights into their implementation techniques beyond their initial learning about engineering design integration, which can be considered as a way of increasing the duration of the instruction.

Integrated Coursework. All but one (Carpenter et al., 2019) of the 22 studies reviewed reported engineering design integration into existing courses as part of their instruction efforts through various strategies. Some of the reviewed studies reported their integration efforts through a content-based perspective, such as dedicating sections of the engineering instruction to the topic of engineering design integration (Antink-Meyer et al., 2023; Capobianco et al., 2022; Estapa & Tank, 2017; French & Burrows, 2018; Hammack & Vo, 2022; Menon et al., 2023;

Menon & Azam, 2021; Mumba et al., 2023; Nesmith & Cooper, 2021; Pleasants et al., 2019, 2020; Ryu et al., 2019). Other studies reported their integration of engineering into science teaching through an activity-based approach (Capobianco & Radloff, 2022; Kaya et al., 2019; Kim et al., 2019; Maiorca & Mohr-Schroeder, 2020; Perkins Coppola, 2019; Tank et al., 2020; Webb & LoFaro, 2020; Wendell, 2014; Yesilyurt et al., 2021).

For example, Pleasants et al. (2019) integrated engineering into existing course to understand how elementary PSTs prioritize different student learning outcomes when integrating engineering into science instruction. The integrated coursework involved workshops, engineering design activities, the nature of engineering (NOE), and collaboration with engineering graduate students, focusing on distinguishing science (understanding the natural world) from engineering (technological solutions for human problems). Despite limited preparation to teach engineering, most PSTs prioritized engineering practices and NOE in their instruction. The study also found that many PSTs focused on the EDP, which may oversimplify engineering and lead to shallow learning objectives. The research highlights the need for the accurate conveyance of the NOE in teacher preparation and curriculum materials and proper guidance on engineering concepts for K-12 students.

The objective of Maiorca and Mohr-Schroeder's (2020) study was to explore how elementary PSTs developed integrated STEM lesson plans using the engineering design process, with a focus on teacher training in STEM. Integrated STEM lesson plans were defined as those containing open-ended activities using the engineering design process to teach math, science, and/or technology, incorporating elements of the Framework for Quality K-12 Engineering Education (FQEE; Moore et al., 2014). They did activities like the Marshmallow Challenge, the Fluor Engineering Design Challenge, and robotics challenges to learn engineering integration into STEM. The study found that while integrating science, math, and engineering posed challenges, most PSTs successfully integrated engineering and math but struggled with science integration. The use of engineering design as a context for integration helped PSTs identify connections among content areas, and teamwork was consistently included in the lesson plans. However, PSTs lacked experience in integrated STEM activities, leading to challenges in describing how students would communicate their models. The study recommended providing more support and guidelines for PSTs in STEM education and highlighted the importance of engineering for integrating science, technology, and math in classrooms.

The Tank et al. (2020) study aimed to explore how elementary PSTs put engineering design-based instruction into practice after participating in engineering professional development, focusing on the presence of engineering and engineering design characteristics. The research was guided by two questions and used various frameworks, including the K-12 Framework for Science Education (NRC, 2012) and the Next Generation Science Standards (NGSS Lead States, 2013), as well as the FQEE (Moore et al., 2014). The study involved 20 elementary school triads, comprising a PST, a cooperating teacher, and an engineering graduate student, and the data collected from them were analyzed using the FQEE as a lens. The PSTs were introduced to engineering integration coursework focusing on designing lessons around engineering challenges, such as the Hexbug design challenge. The outcomes revealed four main ways PSTs in triads implemented engineering design-based instruction and identified six important characteristics for high-quality implementation. The study suggests that professional development should focus on explicitly identifying and scaffolding these characteristics to support high-quality instruction in elementary classrooms, aligning with national reforms and research recommendations in STEM integration.

In summary, the studies reviewed in this section highlighted the significance of integrating engineering design into science teaching. Despite the challenges faced by educators, efforts to integrate engineering design into science methods courses and in K-12 science classrooms were prevalent in most of the studies. For example, Pleasants et al. (2019) emphasize the importance of prioritizing engineering practices and the nature of engineering (NOE) in elementary science classroom teaching while also calling for better preparation of teachers in accurately conveying the NOE and providing guidance on engineering concepts. Maiorca and Mohr-Schroeder (2020) also underscore the benefits of using engineering design as a context for integration to help teachers identify connections among content areas and promote teamwork while emphasizing the need for more support and guidelines for PSTs in STEM education. Similarly, Tank et al. (2020) emphasize the importance of identifying and scaffolding key characteristics of engineering design-based instruction for elementary PSTs, aligning with national reforms and research recommendations in STEM integration. These studies collectively advocate for comprehensive and effective integrated models of intervention for engineering in teacher preparation and promote engineering design implementation in science classrooms.

Field Experience. In this review, fourteen studies (Capobianco et al., 2022; Capobianco & Radloff, 2022; Carpenter et al., 2019; Estapa & Tank, 2017; French & Burrows, 2018; Maiorca & Mohr-Schroeder, 2020; Menon et al., 2023; Menon & Azam, 2021; Nesmith & Cooper, 2021; Perkins Coppola, 2019; Pleasants et al., 2019, 2020; Ryu et al., 2019; Tank et al., 2020) included field experiences in their engineering intervention in teacher education programs. These experiences ranged from one week to one semester (about 16 weeks) of PSTs' teaching placement in schools. For example, Maiorca & Mohr-Schroeder (2020) reported a 1-week STEM camp experience for their PSTs. Four studies (Estapa & Tank, 2017; Pleasants et al., 2019, 2020;

Tank et al., 2020) adopted the triads method (combination of the PST, cooperating teacher, and engineering fellow) and had field placements that lasted for sixteen weeks. Menon and Azam's (2021) intervention was for three – 45-minute sessions and Carpenter's (2019) was for five weeks with an option to participate for the rest of the academic year. The field experience in Nesmith and Cooper's (2021) study lasted for 13 weeks, with the PSTs required to teach for an hour each week. As for Perkins Coppola (2019), the field placements for the engineering units were for two days across eleven weeks.

Perkins Coppola (2019) focused on examining the impact of engineering mini units (EMUs) on preservice elementary teachers' self-efficacy and outcome expectancy in teaching engineering. The integration of EMUs into a science methods course involved three main activities: participating in an exemplar EMU, writing and revising an EMU, and teaching the EMU to elementary students during a field experience. The analysis of four semesters of data indicated that the integration of EMUs led to significant improvements in PSTs' self-efficacy scores in three out of four constructs: engineering pedagogical content knowledge, engineering engagement self-efficacy, and engineering disciplinary self-efficacy. The field experience component played a critical role in enhancing self-efficacy, especially in the area of engineering disciplinary self-efficacy, which required modelling and practicing classroom management strategies. However, the study found that the improvement in engineering outcome expectancy was not as significant, possibly due to misconceptions about what it means to affect student learning of engineering. Further iterations of the EMU in the science methods course should aim to address this issue and improve PSTs' engineering outcome expectancy. The study highlighted the importance of providing PSTs with positive experiences in engineering design, both as participants and teachers during field experiences, to generate enthusiasm and build confidence.

The study had limitations, including a limited sample and self-reported data, and future research should explore the relationship between mindset and teaching engineering self-efficacy (TES) and examine ways to improve engineering outcome expectancy.

Menon et al. (2023) aimed to investigate PSTs-integrated STEM teaching self-efficacy and conceptions of STEM teaching and learning. The results strongly suggested significant positive gains in integrated STEM self-efficacy and positive shifts in PSTs' conceptions and attitudes about STEM from the beginning to the end of the semester. The exposure to STEM experiences during field experiences and methods courses helped PSTs become more comfortable and confident in planning and designing STEM lessons, as well as increased their intentions to teach STEM topics in the future. The field experiences provided a suitable context for positive changes in conceptions and self-efficacy for integrated STEM, especially when STEM educators engaged in regular discourse and co-designed the STEM pathways and curriculum across the methods courses.

Additionally, the field experiences from Menon et al. (2023) exposed PSTs to positive role models, such as classroom teacher mentors, supporting young learners in STEM, which may have contributed to positive changes in PSTs' perspectives about STEM learning, including attitudes towards encouraging young girls in STEM. The study suggested that PSTs need additional practice, support, and partnerships with schools where field experiences involve observing positive role models, which could enhance PSTs' engineering design teaching self-efficacy. However, the study acknowledged limitations, including the unique structure of the STEM semester and the need for further research on the validity and reliability of the instrument used to measure integrated STEM self-efficacy. Nevertheless, the results imply the importance of explicit STEM instruction in an integrated way and have significant implications for PST preparation programs, emphasizing the need to involve PSTs in explicit discussions about integrated STEM challenges and practices during field experiences. Future research may explore the long-term effects of self-efficacy development and consider diverse participant backgrounds and demographics to understand their impact on self-efficacy development.

The field experiences reported in Mumba et al. (2023), specifically the implementation of engineering design-integrated science (EDIS) instructional units by science PSTs, played a significant role in influencing the outcomes of the study. The results showed that pre-service teachers were able to successfully develop EDIS instructional materials, integrating both science and engineering practices and design skills. The PSTs approached engineering design as a foundational component of the instructional units rather than treating it as an add-on or culminating activity. This explicit approach to engineering integration was consistent with the intervention model and NGSS guidelines. In Mumba et al. (2023), PSTs were immersed in authentic EDIS instructional activities and resources that explicitly addressed NGSS practices and the engineering design process. This exposure motivated the PSTs to learn more about engineering design, especially since current science education reforms require them to incorporate engineering in science instruction. The findings suggest that the explicit instructional approach to engineering design in science teacher education can increase the opportunity for teachers to develop sound instructional planning skills for EDIS lessons. It is likely to have a positive impact on their instructional practices and, subsequently, on students learning of science and engineering. While the study's findings cannot be generalized due to the small number of participants, they lay the foundation for future research in science teacher education.

Field experiences, particularly the practicum and practicum school environment, played a role in shaping the outcomes of Ryu et al.’s (2019) study on integrated STEM education for

PSTs. Throughout these experiences, STEM education students employed diverse approaches to developing integrated STEM lessons, influenced by their previous experiences, personal interests, and disciplinary backgrounds. The field experiences brought to light various challenges faced by pre-service teachers in implementing integrated STEM education, including existing school culture and structure, limited knowledge in STEM fields, and a lack of role models. These challenges highlighted the powerful discourse communities within schools that could potentially hinder the adoption of innovative teaching practices like integrated STEM approaches. However, despite these obstacles, the field experiences also allowed pre-service teachers to recognize the potential and significance of STEM integration. They considered crucial factors like students' interests, curricular standards, and local contexts while crafting successful integrated STEM lessons. Internet usage played a vital role as a major technological tool in accessing and coordinating existing resources shared by experienced educators.

Field experiences, specifically the practicum and practicum school environment, have proven to be a vital component in the success of several studies on integrated STEM education for pre-service teachers. These experiences have been shown to play a significant role in shaping the teaching practices of pre-service teachers, helping them incorporate novel teaching methods, such as culturally responsive teaching and inclusion for special education students. The field experiences have also provided opportunities for pre-service teachers to observe and learn from positive role models, contributing to positive shifts in their attitudes and conceptions about STEM teaching and learning. Moreover, the field experiences have served as a platform for pre-service teachers to immerse themselves in authentic STEM instructional activities and resources, explicitly addressing the guidelines and expectations of STEM education reforms. This exposure has motivated pre-service teachers to embrace engineering design as a foundational component of instructional units rather than treating it as an add-on or isolated activity. The explicit instructional approach to engineering design in science teacher education has been found to enhance pre-service teachers' instructional planning skills for integrated STEM lessons.

Despite the challenges encountered during field experiences, such as existing school culture, the findings across the reviewed studies suggest that these experiences offer valuable insights and opportunities for growth in pre-service teachers. As a result, teacher education programs should continue to emphasize the importance of field experiences and consider leveraging partnerships with schools and teachers committed to engineering design integration, providing valuable mentoring and support. Furthermore, implementing explicit engineering design instruction during field experiences and engaging in regular discourse with STEM educators can further enhance pre-service teachers' abilities to design and implement effective integrated engineering design lessons.

Tasks for Learning to Teach Engineering Design Integrated Science Lessons

Analyzing Beliefs and Forming New Visions of Teaching Science Through Engineering Design. Twelve (12) of the 22 papers reviewed included the analysis of PST beliefs, conceptions, and/or perceptions of engineering and engineering design integration (Capobianco et al., 2022; Capobianco & Radloff, 2022; Carpenter et al., 2019; Hammack & Vo, 2022; Kaya et al., 2019; Kim et al., 2019; Menon et al., 2023; Nesmith & Cooper, 2021; Perkins Coppola, 2019; Pleasants et al., 2020; Wendell, 2014; Yesilyurt et al., 2021). For example, Hammack and Vo (2022) sought to investigate how case-based learning and the Draw an Engineering Teacher Test (DAETT) can help PSTs broaden their understanding of engineering education. The authors noted that the PSTs were able to expand their knowledge and broaden their conceptions of engineering education. Nonetheless, they faced challenges in distinguishing between teaching science and engineering. The study also highlighted how many PSTs still held misconceptions about engineering, emphasizing the need for PSTs to understand effective engineering teaching in the classroom. The authors found that some PSTs lacked a proper conception of engineering education, while others demonstrated a strong conception in their drawings. Using similar method, Draw an Engineer Test (DAET), Pleasants et al.'s (2020) reported that the professional development program had a positive impact on PSTs' conceptions of engineering, as demonstrated by improved accuracy scores over time for both PSTs and cooperating teachers in the treatment group. Both studies discussed how PSTs' understanding of engineering is an essential aspect of their knowledge of the subject and noted that the DAET was used to assess their comprehension and representations of engineering work. However, Pleasants et al.'s (2020) said that PSTs tended to concentrate on the EDP in their depictions, which may have been influenced by the curriculum materials used during professional development. The study emphasizes the importance of selecting curriculum materials that provide a comprehensive and nuanced view of engineering work to support teacher learning.

In a similar study, Wendell (2014) investigated the engagement of PSTs in engineering design activities within an integrated engineering and literature context. The study compared the design processes of PSTs to those of novice and expert engineers on a furniture design task. The author was specifically interested in 'the teachers' framing of their activity, … interested in what kind of "game" they perceive themselves to be playing' (Wendell, 2014, p. 4). This game could either be a classroom game or an engineering game. The results revealed that PSTs displayed stable attention to the engineering design task, focusing primarily on idea generation and judging feasibility at the expense of information gathering, design solution modelling, and detailed evaluation of proposed solutions. In contrast, novice and expert engineers emphasized problem definition and information gathering along with idea generation. This indicates that the PSTs developed new conceptions of engineering teaching. The study suggested instructional implications for pre-service teacher education in engineering, highlighting the need to provide opportunities for PSTs to engage in problem scoping and information gathering to enhance their understanding and practice of engineering design. The findings also raise questions about how the integration of engineering design tasks with literature may impact the demand for information gathering and problem scoping in the design process. The paper proposes possible approaches, such as assigning more open-ended and longer-term engineering design problems, developing engineering case studies, and using scaffolds to support PSTs in engaging in comprehensive engineering design practices.

In their research, Menon et al. (2023) explored ways to support future teachers in developing the knowledge and skills necessary for integrated STEM teaching and learning within teacher preparation programs. The study had two main objectives: (1) to assess the self-efficacy of PSTs in integrated STEM teaching and (2) to gain an understanding of the PSTs' conceptions of STEM teaching and learning as they participated in three concurrent methods courses during a STEM semester. The results showed that PSTs experienced significant positive gains in their self-efficacy for integrated STEM teaching and that their conceptions and attitudes about STEM shifted positively from the beginning to the end of the semester. PSTs' prior experiences influenced their initial perceptions of STEM, while exposure to STEM experiences within the methods courses helped them gain a better understanding of how different disciplines work together in an integrated STEM lesson. The study emphasized the importance of strong partnerships between multi-disciplinary STEM education faculty to design authentic STEM experiences and provided implications for PST preparation programs to support PSTs' smooth transition into their student teaching while addressing biases and stereotypes related to STEM. The findings suggest that explicit instruction in integrated STEM is significant, and PSTs need to observe and practice integrated STEM teaching during field experiences.

The reviewed studies in this section emphasize the significance of beliefs in improving PSTs' integration of engineering design during teacher preparation. Professional development programs positively impact PSTs' conceptions of engineering, but the choice of curriculum materials influences their representations of engineering. The studies underscore the importance of providing PSTs with opportunities to engage in engineering design practices, including problem scoping and information gathering. These opportunities will provide a new platform on which PSTs can begin to develop a different belief structure and perspective about the role of engineering and the EDP in science teaching. Strong partnerships between multi-disciplinary STEM education faculty and authentic STEM experiences positively impact PSTs' self-efficacy and attitudes towards integrated STEM teaching. The research highlights the importance of integrating engineering meaningfully into elementary teacher education and emphasizes the significance of effective engineering teaching theory and practice. The findings underscore the need to provide engineering opportunities in elementary science methods courses to support PSTs' engagement with the engineered world. As such, the findings call for explicit instruction in integrated STEM during teacher preparation programs and exposure to authentic STEM experiences to foster positive shifts in PSTs' attitudes about STEM. Further research is needed on the process of how PSTs develop new visions and beliefs about teaching integrated engineering design in science classrooms, guiding the improvement of teacher preparation programs to support proficient STEM educators.

Developing Science and Engineering Subject Matter and Pedagogical Knowledge and the Demands of Engineering Design. All reviewed papers included this task as part of their intervention in engineering design integration in their teacher preparation programs. Despite the ubiquity of this task, certain studies shared significant details about their efforts at developing PSTs' science and engineering content and pedagogical knowledge, and these are reviewed below. For example, Nesmith and Cooper's (2021) research incorporated a specifically designed engineering unit within an elementary science methods course and supported it in a mathematics methods course, aiming to promote growth in PSTs' understanding, abilities, and self-efficacy related to engineering. The engineering unit involved hands-on experiences with the engineering design process, explicit foci on connections between the work of scientists and engineers, the processes of science, engineering, and mathematics, and the cycles of the engineering design process and the 5E inquiry process. The PSTs recognized the components of the engineering design process and its real-life applicability based on discussions that made explicit connections between science, mathematics, and engineering concepts. While PSTs recognized the value and importance of engineering design integration in science education, they often grappled with problems stemming from limited prior experiences, uncertainties surrounding practical implementation, and concerns about their adequacy in effectively teaching engineering concepts to students. Despite these challenges, the impact on PSTs' knowledge and efficacy was promising, albeit there is still room for improvement, and the researchers planned to explore ways to adapt the engineering unit to further modify PSTs' beliefs, attitudes, and behavior patterns specific to engineering pedagogical content knowledge and engineering teaching self-efficacy. Future research should consider providing opportunities for PSTs to design and implement engineering lessons in schools and focus on measuring their pedagogical content knowledge for EDIS instruction.

In tandem with this, French and Burrows (2018) conducted a study to enhance the teaching methods of secondary science for PSTs. The courses incorporated various interventions, including developing general lesson plans, researching misconceptions held by K-12 students, creating sample teaching videos, analyzing data using probe ware, programming robotics, and integrating engineering and computer science into STEM K-12 classrooms. The courses focused on content knowledge, content pedagogy, learning environments, safety, impact on student learning, and professional knowledge and skills. The PSTs were assessed on their instructional planning through ideal lesson plan scenarios, and the data showed that many PSTs included opportunities for students to use scientific instruments and technology and work collaboratively. However, the Assessment and Inquiry Science (ASI) process, such as developing testable questions, identifying problems, and disseminating results, was less emphasized, indicating areas for improvement. The study suggests that PSTs need explicit instruction on ASI components and opportunities to participate in research projects to better prepare them for their future K-12 classrooms.

Expanding on this theme, Yesilyurt et al. (2021) reinforced the significance of hands-on engineering challenges, explicit instruction on EDP, and discussions on teaching engineering concepts. Participants were pre-service elementary teachers enrolled in a science teaching methods course. The study found that cognitive content mastery, cognitive pedagogical mastery, and cognitive self-modelling were the most significant sources of engineering teaching self-efficacy among the PSTs. Their integrated engineering design context contributed to their improved teaching efficacy. Likewise, in Nesmith and Cooper's (2021) study, PSTs also recognized the significance of integrating engineering design into science instruction but faced challenges rooted in a lack of prior exposure to engineering concepts, misconceptions about the subject, and apprehensions about transferring their knowledge to classroom contexts. Hence, the study suggests the importance of integrating engineering into methods courses, providing teaching contexts for engineering experiences, and developing integrated courses to effectively prepare PSTs in science and engineering education.

Mumba et al. (2023) further expanded on the integration of engineering design into science instruction by applying the informed engineering design model (Chiu et al., 2013) in a one-year graduate secondary science teacher education program. The intervention aimed to enhance PSTs' comprehension and application of disciplinary core ideas, crosscutting concepts, and science and engineering practices, as well as their understanding of the EDP. The PSTs engaged in hands-on EDIS activities, created EDIS teaching and learning resources, and developed teacher guide manuals for EDIS instruction. Results show that PSTs developed an understanding of engineering design and the engineering design integration process. A parallel line of research is represented by Menon et al.'s (2023) research conducted in a redesigned elementary STEM semester at a research-intensive university. They enacted three concurrent courses centered on integrated STEM connections: mathematics, science and engineering, and technology or Innovative Learning Technologies (ILT) methods. The courses focused on content areas relevant for PSTs to experience STEM connections across disciplines and solve engineering design challenges. The study found that the STEM semester significantly improved pre-service teachers' integrated STEM teaching self-efficacy and positively shifted their conceptions and attitudes about STEM. The integrated and interdisciplinary approach to teaching and learning in the STEM semester contributed to the positive gains in subject matter and pedagogical knowledge for integrated STEM among pre-service teachers.

In a related study, Estapa and Tank (2017) focused on enhancing elementary PSTs' preparedness to teach STEM subjects through the infusion of engineering design concepts into an elementary teacher preparation program. The program included a triad partnership between PSTs, cooperating teachers, and engineering graduate students, aiming to bring different expertise to the classroom. Participants underwent a week-long summer workshop to provide support for STEM integration, with a specific focus on engineering design-based learning. The engineering design challenge, a key component of the workshop, helped participants extend their knowledge and apply it in a collaborative context. While the study showed success in identifying STEM content connections within engineering design activities, there was a decrease in math and science content during enactment. The findings highlighted the need for more emphasis on connecting content within lessons and providing support for teachers to enact integrated STEM curricula effectively. Additionally, the study suggests the importance of positioning engineering as academic content rather than solely a skill or practice to foster robust integration of STEM in elementary classrooms.

The reviewed literature underscores the pivotal role of PSTs’ subject matter and pedagogical knowledge in effectively integrating engineering design into science teaching. Each study contributes insights into specific strategies, highlighting the need for well-conceived instructional interventions to increase PSTs' skills and support them in weaving engineering design into their teaching repertoire, thereby fostering a profound understanding and appreciation of STEM subjects. In summary, the reviewed studies emphasize the fundamental role of PSTs’ subject matter and pedagogical knowledge in effectively integrating engineering design into science teaching. Nesmith and Cooper's (2021) research highlighted the importance of explicit connections between science, mathematics, and engineering concepts to enhance PSTs' understanding and self-efficacy related to engineering. French and Burrows' (2018) study indicated the need for explicit instruction on ASI components to improve PSTs' instructional planning, and Yesilyurt et al.'s (2021) research emphasized the significance of hands-on engineering challenges and explicit instruction on the engineering design process to enhance PSTs' teaching efficacy. Mumba et al.'s (2023) intervention successfully integrated science and engineering practices into PSTs' instructional units, and Menon et al.'s (2023) interdisciplinary approach in the STEM semester positively impacted PSTs' integrated STEM teaching self-efficacy and attitudes. Estapa and Tank's study underscored the importance of connecting content within lessons and positioning engineering as academic content for robust integration of STEM in elementary classrooms. These findings, despite the challenging demands the PSTs had to overcome in their learning and implementing of integrated engineering design science instruction, collectively highlight the need for well-designed instructional strategies and content-focused interventions. These efforts will support PSTs in effectively integrating engineering design into their teaching practices, promoting a deeper understanding and appreciation of STEM subjects. More research is needed to measure PSTs' development of pedagogical content knowledge and its impact on instructional practices.

Forming an Understanding of Diverse Learners in Science and Engineering Design Classrooms. Only two studies (Capobianco & Radloff, 2022; Webb & LoFaro, 2020) incorporated this learning task into their intervention program. This task for learning ensured that the PSTs developed a comprehensive understanding of the diversity among their future students. Though the two studies had different approaches, their objective was the same - to prepare PSTs to leverage the latent potential that K-12 students harbor. By doing so, the PSTs could provide effective EDIS teaching that caters to the diverse needs of their students. For example, Capobianco and Radloff (2022) adopted a theoretical framework known as ‘ambitious science teaching’ to improve the understanding of diverse learners among PSTs. This approach requires PSTs to engage in practices that are proximal to the practices of a profession, focusing on adaptive instruction that caters to students' needs and thinking while maintaining standards for participation and performance. The authors emphasized the importance of responsiveness to student thinking and reasoning, recognizing students as sense-makers with valuable ideas. Capobianco and Radloff (2022) also introduced the PSTs to engineering design-based science instruction, which requires the teacher to adapt instruction to students' ideas, needs, and thinking as they progress through different design phases. The PSTs were introduced to, engaged in, planned for, and tested these ambitious practices for engineering design-based science instruction in an elementary science methods course.

The outcomes of the Capobianco and Radloff (2022) study were aligned with the objective of improving PSTs' understanding of K-12 student diversity. The PSTs demonstrated promising intentions to organize and plan for engineering design-based science teaching. This indicated their capacity to plan for ambitious engineering design-based science teaching that placed emphasis on one or more core practices, such as responsiveness to students’ reasoning, discourse-based practice, and eliciting student ideas. Three trajectories of practice emerged from PSTs' implementation: ‘adaptive approximations for ambitious design-based science teaching practices, compartmentalizing a practice within a design phase, and using delivery pedagogies as a guise for ambitious design-based science teaching’ (Capobianco & Radloff, 2022, p. 1636). The authors determined that the PSTs enacted diverse trajectories into and around the set of instructional practices offered to them in the course, demonstrating a range of approaches to understanding and teaching diverse learners.

Alternatively, Webb and LoFaro (2020) adopted a theoretical framework grounded in Bandura's social cognitive theory (Bandura, 1986), focusing on the construct of self-efficacy. They applied this theory to the teaching of engineering practices, suggesting that a course focused on engineering could strengthen elementary PSTs' engineering self-efficacy, which can influence their teaching of engineering practices. The authors identified four sources of self-efficacy: mastery experiences, vicarious experiences, verbal persuasion, and emotional and physiological states. They further expanded on these sources, introducing concepts like cognitive content mastery and cognitive pedagogical mastery. The authors designed a course that included activities, discussion, reflection, and assignments that leveraged these sources of self-efficacy. The course involved PSTs teaching engineering practices to elementary students, providing them with enactive mastery experiences. The course also included simulated modelling, where the instructor modelled the teaching of engineering challenges, and the PSTs played the role of elementary students.

Webb and LoFaro's (2020) results underscored significant improvements in PSTs' engineering self-efficacy, as measured across all three subscales of the Teacher Sense of Self-Efficacy Survey (TSES) instrument. A key factor contributing to these gains was cognitive pedagogical mastery, which was fostered through a blend of engineering challenge activities and educational resources such as textbooks, articles, lectures, and curriculum. Importantly, the integration of culturally responsive teaching practices within the engineering curriculum emerged as a pivotal element in enhancing cognitive pedagogical mastery. This approach not only enriched the PSTs' understanding of diverse learners but also equipped them with the skills to effectively teach engineering practices in a manner that respects and acknowledges cultural diversity. Furthermore, the study found that vicarious experiences, particularly in the form of simulated modelling and the reduction of emotional fears associated with teaching engineering practices, were the second most influential factors in boosting engineering self-efficacy. However, it was the integration of culturally responsive teaching practices that truly set this study apart. This approach was instrumental in preparing PSTs to teach engineering in diverse classrooms, thereby aligning with the study's objective of improving PSTs' understanding of K-12 student diversity.

To sum up, the studies by Capobianco and Radloff (2022) and Webb and LoFaro (2020) emphasized the importance of providing PSTs with the necessary skills and knowledge to effectively teach EDIS in diverse classrooms. Capobianco & Radloff's approach of ‘ambitious science teaching’ and Webb & LoFaro's emphasis on self-efficacy, with a focus on culturally responsive teaching practices, aim to improve PSTs' ability to adapt to the diverse needs of their students. These positive outcomes reveal the potential of such approaches in preparing PSTs for diverse classrooms, enabling them to effectively teach EDIS. The integration of culturally responsive teaching practices was found to be a crucial factor in enhancing PSTs' understanding of diverse learners, enriching their skills to teach engineering practices that respect and acknowledge cultural diversity. Yet only two of the studies reviewed addressed this element of the framework. Additionally, there is a lack of focus on preparing PSTs for integrated engineering design instruction in classrooms with special education and emergent bilingual students. It will be difficult to assert that student diversity is being addressed in engineering design integration teacher preparation when these important groups of students are not being considered. Therefore, we suggest that teacher preparation programs should incorporate these practices to foster a learning environment that acknowledges and respects student diversity, ultimately promoting inclusivity and effectiveness in education.

Growing a Beginning Repertoire for Engineering Integrated Science Instruction. All the studies save for one (Hammack & Vo, 2022) included in their interventions an objective to help PSTs to begin developing a repertoire for EDIS instruction. These studies generally addressed this task through either emphasis on instructional planning, implementation of instruction, or both. Most studies placed their emphasis on instructional planning (Antink-Meyer et al., 2023; Capobianco & Radloff, 2022; French & Burrows, 2018; Menon et al., 2023; Menon & Azam, 2021; Mumba et al., 2023; Nesmith & Cooper, 2021; Pleasants et al., 2020; Wendell, 2014; Yesilyurt et al., 2021). Four studies highlighted their efforts at improving the PSTs' implementation of engineering design integration repertoire (Estapa & Tank, 2017; Kaya et al., 2019; Pleasants et al., 2019; Tank et al., 2020) while the other seven studies indicated emphasis on both instructional planning and implementation (Capobianco et al., 2022; Carpenter et al., 2019; Kim et al., 2019; Maiorca & Mohr-Schroeder, 2020; Perkins Coppola, 2019; Ryu et al., 2019; Webb & LoFaro, 2020).

For example, Carpenter et al.'s (2019) study was framed by a situated perspective on teacher learning, focused on the development of PSTs' understanding and implementation of the NGSS's science and engineering practices. These experiences were seen as social learning environments where potential and preservice teachers could build their repertoire for science instruction and engineering design. The authors examined the understanding of PSTs at two points in the initial preparation phase—undergraduate-level prospective teachers and graduate-level PSTs. They found that the potential and preservice teacher participants described the practice of developing and using models in multiple ways, aligning with 16 out of 22 modelling competencies in their coding scheme.

However, the potential and PSTs' understanding of science and engineering practices of developing and using models was found to be varied. This variation was seen as an opportunity for growth in their instructional planning and implementation repertoire. The teachers' understanding of these practices was used as a starting point to build upon and strengthen their knowledge and implementation of these practices in their instructional planning. The authors also found differences in understanding and implementation of the practice of modelling by group and practicum context. This suggests that the stage of teacher preparation and the specific context of the practicum experience can influence the development of the teachers' instructional planning and implementation repertoire. For instance, prospective teachers who were at the beginning stages of exploring teaching as a career had a broader understanding of the practice of developing and using models, which could be seen as a wider repertoire for instructional planning and implementation.

Capobianco et al. (2022) adopted a theoretical framework of ‘Teacher as Learner’ to improve the repertoire of PSTs for science instruction and engineering design. The framework views learning about teaching as situated, social, and distributed. The PSTs participate in content-rich design tasks that mirror essential practices for engineering design-based science teaching. These tasks are modelled by the instructor to reinforce knowledge, skills, and situations that represent potential real-world classroom applications. The PSTs then collaborate to develop, implement, and reflect upon an engineering design task in their field placement classrooms. They engaged with other educators and PSTs to experiment, test, and reflect on their formative knowledge related to teaching engineering design-based science lessons. Throughout the semester, the Capobianco et al. (2022) study found that PSTs engaged in scaffolded activities that had a positive impact on their comprehension and views of engineering design. These activities resulted in a greater understanding of concepts, fresh teaching perspectives, and an improved attitude toward engineering design-based scientific instruction. As a result, the course effectively prepared PSTs to teach engineering design in classrooms.

Some of the activities included in Kim et al.'s (2019) engineering design integration intervention had the effect of improving PSTs' repertoire for instructional planning and implementation. The instructional planning involved the design of a course that integrated engineering design activities, class discussions, and interviews. The course was conducted over two years and involved observation of PSTs' activities. The PSTs were engaged in diverse STEM activities, including designing and building a 'candy grabber' and distinguishing between science and engineering based on real-life scenarios. The instructional implementation involved the PSTs actively participating in these activities, and their experiences were documented through assignments and reflective journals. The researchers observed the PSTs' activities and conducted interviews at the end of the course to understand their perspectives and trace their self-reported conceptual change.

The outcomes of Kim et al. (2019) showed that the PSTs initially had little knowledge about teaching engineering content. However, their confidence in teaching engineering increased by the end of the semester, which can be attributed to their improved repertoire for science and engineering design teaching. The study demonstrated that the instructional planning and implementation of engineering design activities in the course helped the PSTs to acquire both types of knowledge – an understanding of engineering as a content area and as an aspect of science teaching. The PSTs' experiences with both observing and enacting teaching are an important factor in the growth of their confidence in teaching engineering within the context of a science classroom.

These studies collectively highlight the approach to developing PSTs' repertoire for science and engineering design instruction. Studies by Carpenter et al. (2019), Capobianco et al. (2022), and Kim et al. (2019) demonstrate that a focus on instructional planning and implementation can significantly enhance PSTs' confidence and proficiency in teaching diverse students. The strategic use of social learning environments, real-world applications, and reflective practices were found to be particularly effective in this regard. These studies also underscore the importance of contextual factors, such as the stage of teacher preparation and the practicum experience, in shaping PSTs' instructional repertoire. Furthermore, the studies reveal that while PSTs can significantly improve their understanding and implementation of science and engineering practices, there is often considerable variation in these improvements. This suggests that ongoing support and tailored interventions may be necessary to ensure that all PSTs are adequately prepared for the challenges of teaching diverse students. Ultimately, these findings underscore the importance of a comprehensive and nuanced approach to teacher preparation, one that not only equips PSTs with the necessary knowledge and skills but also fosters their confidence and adaptability in the face of diverse teaching contexts.

Identifying Tools to Study Engineering Design Integrated Science Instruction and Its Impact on Student Learning. Twelve (12) of the 22 studies addressed this task in their interventions to varying degrees (Antink-Meyer et al., 2023; French & Burrows, 2018; Kaya et al., 2019; Menon & Azam, 2021; Mumba et al., 2023; Nesmith & Cooper, 2021; Perkins Coppola, 2019; Pleasants et al., 2020; Ryu, 2015; Tank et al., 2020; Webb & LoFaro, 2020; Yesilyurt et al., 2021). Specifically, in Mumba et al. (2023), the PSTs were introduced to

Engineering Teaching Kits (ETKs) (Richards et al., 2007) and other online resources like teachengineering.org during the intervention. They were also involved in a resource collection assignment to create a collection of digital and non-digital engineering design resources they would use to teach EDIS lessons. Similarly, Webb and LoFaro (2020) mentioned providing PSTs with resources and strategies to integrate culturally responsive engineering practices and how to teach engineering using everyday materials, indicating that participants were given tools to study engineering design integration and student learning. Following this, a deeper analysis of how this task influenced the outcomes in some of the reviewed studies.

On another note, Ryu et al. (2019), the PSTs utilized a variety of instructional tools and resources to develop integrated STEM lessons. These included their own experiences, classroom observations, and the internet. The internet was a major tool used extensively for various purposes such as identifying useful hands-on science experiments and/or design challenges, finding existing integrated STEM lesson plans, conducting scholarly research relevant to the selected lesson topics, and discovering contexts that may intrigue their students. Interestingly, the PSTs' use of the internet is a clear demonstration of how pedagogical practices can be mediated by technology tools. This suggests that successful lesson planning can also be facilitated by the effective and critical use of online resources. Furthermore, the PSTs were able to select, modify, interpret, and use multimodal texts for teaching, demonstrating their information literacy, multimodal literacy, and critical analysis of existing curricula.

Building on that, according to Ryu et al. (2019), the use of these instructional tools and resources led to the development of diverse and engaging STEM lessons. For instance, the PSTs were able to incorporate various aspects of STEM integration that they believed to be appropriate for adolescents, such as hands-on activities, relevant contexts, and real-world stories. They also considered content standards and tried to identify aspects relevant to content standards in the selected hands-on activity. However, the study also highlighted challenges in implementing integrated STEM education due to existing school structure and instructional practices, limited interdisciplinary understandings, and the absence of role models. These challenges suggest that while instructional tools and resources can facilitate the development of integrated STEM lessons, their effective implementation also depends on the broader educational context, including school culture, curriculum structure, and teacher professional development.

In a similar vein, Kaya et al. (2019) utilized a variety of instructional tools and resources to enhance the teaching methods course for PSTs. The primary tool used was TinkerCAD, an online 3D design software that was instrumental in teaching the EDP. The PSTs were given the practical task of designing a keychain, which required them to apply the principles of EDP, thereby providing them with hands-on experience. Moreover, this tool allowed them to visualize their designs, receive feedback, and make necessary improvements, thereby enhancing their understanding of the EDP. Beyond this, in addition to TinkerCAD, the study also utilized a Makerbot Replicator + 3D printer. This tool provided the PSTs with a tangible outcome of their designs, further solidifying their understanding of the EDP. The 3D printer also served as a teaching tool for the instructor, who used it to demonstrate the practical aspects of 3D printing, including troubleshooting and maintenance.

Likewise, another significant resource used in the Kaya et al. (2019) study was Thingiverse Education, an online platform where teachers share lesson plans that integrate 3D printing in a broad range of subjects. This resource provided the PSTs with a wealth of ideas and strategies for integrating 3D printing into their future classrooms. As a result, the outcomes of the study showed that these instructional tools and resources significantly improved the PST's engineering teaching efficacy beliefs. The hands-on experience with 3D design and printing, coupled with the resources provided, helped the PSTs understand the EDP better. They also reported that these tools and resources were effective in introducing the EDP to elementary students. This suggests that the use of these instructional tools and resources enhanced not only the PST's understanding of the EDP but also their confidence in teaching it.

In a similar study, Yesilyurt et al. (2021) provided PSTs with a variety of instructional tools and resources to enhance their teaching efficacy in engineering. The course was designed with a strong emphasis on the use of instructional tools and resources, including engineering design challenges, Lego Mindstorms EV3 Educational Robotics kits, and a wide variety of curricular materials. The engineering design challenges served as practical tools for the PSTs to experience the engineering process firsthand. They were guided through the entire engineering design process, from brainstorming and sketching design options to constructing prototypes and refining their designs based on empirical data. The use of Lego Mindstorms EV3 Educational Robotics kits was another significant instructional tool. These kits allowed the PSTs to engage in the engineering design process through programming, providing a tangible and interactive way to understand and apply engineering concepts.

Furthermore, in addition to these hands-on tools, the Yesilyurt et al. (2021) course also provided a wide range of curricular materials to support the PSTs' learning. These included sample lessons, sample engineering challenges, YouTube channels with videos of sample engineering lessons, and children’s engineering books. These resources provided the PSTs with a rich source of information and ideas to draw upon in their instructional planning and implementation. Consequently, the outcomes of the study showed that these instructional tools and resources significantly improved the PSTs' engineering teaching self-efficacy beliefs. The use of these tools and resources not only enhanced the PSTs' understanding of engineering concepts but also gave them the confidence to teach these concepts effectively. Yet, the study also found that while the PSTs felt more confident in their ability to teach engineering, they were less certain about the effectiveness of their teaching, suggesting that further support and resources may be needed to help them translate their knowledge and skills into effective classroom practice.

An important part of this learning task is the role reflections play as a tool to study EDIS instruction. Both Antink-Meyer et al. (2023) and Menon and Azam (2021) recognized the significance of reflective practices in the teaching process. In the study by Antink-Meyer et al., reflections through curiosity journaling stimulated ideas and curiosity but did not significantly enhance teaching confidence. In contrast, Menon and Azam's study found reflections crucial in shaping preservice teachers' identities, serving as a tool for introspection and growth. For Antink-Meyer et al., reflections were employed as a tool to gauge the curiosity of PSTs about scientific phenomena through the medium of curiosity journaling. This was devised to prompt PSTs to become more observant of their environments and encourage them to contemplate the scientific or engineering concepts and practices present in their daily lives. On the other hand, Menon and Azam placed emphasis on reflections as a medium for understanding and analyzing the PSTs' evolving perceptions of science teaching. For them, reflection was a structured activity that comprised writing science autobiographies and reflections on field teaching experiences. This approach was believed to help the teachers emerge as ‘reflective practitioners,’ enabling them to delve deeper into their teaching journey and experiences.

To sum up, the reviewed studies collectively underscore the pivotal role of instructional tools and resources in enhancing the pedagogical skills of PSTs for teaching EDIS lessons. The studies by Ryu et al. (2019), Kaya et al. (2019), and Yesilyurt et al. (2021) all demonstrate that the strategic use of appropriate resources can significantly improve PSTs' understanding of complex concepts, their ability to plan and implement, and their confidence in teaching EDIS lessons. Furthermore, the use of online resources, hands-on tools, and curricular materials not only enriched the PSTs' knowledge base but also provided them with practical, real-world experiences that are crucial for the effective teaching of EDIS lessons. However, these studies also highlight the challenges that PSTs face in implementing integrated STEM education, suggesting the need for a supportive educational context that includes ongoing professional development and a conducive school culture. As seen in the studies by Antink-Meyer et al. (2023) and Menon and Azam (2021), reflections and critical self-awareness further complement these instructional tools, emphasizing the importance of integrating both tangible resources and introspective practices. Therefore, while the improvement in PSTs' abilities is evident, the successful translation of these skills into classroom practice requires a holistic approach that considers the broader educational landscape.

Conclusion and Implications

The purpose of this paper was to review the extant research on teacher education interventions focused on preparing PSTs to teach science using engineering design. Specifically, we wanted to investigate in what ways intervention programs are addressing structural and content components, which we call tasks for learning, which we believe are key elements in PSTs' preparation. The analysis found that interventions varied in their approach to the structure and task-related aspects of the analysis framework used, which affected the outcomes of the reviewed studies. However, all except one intervention (Carpenter et al., 2019) included engineering design instruction, and most interventions included field experiences. These interventions ranged in characteristics from researcher-designed instructional models and engineering design challenges to school field trips and triad-focused interventions. One of the key findings was that the length of interventions varied. Despite the different foci of the studies, longer intervention durations appeared to lead to better outcomes.

The tasks for learning listed in the analysis framework were also addressed in different ways and extents. For example, interventions addressed PSTs' engineering design subject matter knowledge in various ways. All but one study addressed the repertoire for engineering and science instruction (Hammack & Vo, 2022). Results generally suggested that PSTs improved their abilities or self-efficacy to integrate engineering design and transfer their knowledge of key practices into instructional action in science classrooms. However, some tasks, such as providing PSTs with tools for evaluating EDIS instruction and student learning, supporting PSTs in examining their beliefs about teaching science using engineering design, and providing PSTs with an understanding of how to teach engineering design in diverse classrooms, were understudied in the studies reviewed. For example, most teacher education programs did not provide PSTs with opportunities to learn how to teach EDIS lessons in diverse classrooms in schools. These are science classrooms that have special education students, English language learners, and minority students. Yet, research continues to show that K-12 classrooms will be more diverse than ever before (Kang, 2017; Rodriguez et al., 2017). PSTs understanding and appreciating the cultural diversity in K-12 science classrooms will be beneficial to their effective integration of engineering design into science instruction. These benefits stem from actions like the better utilization of K-12 students’ funds of knowledge, which provides stronger connections to science concepts for K-12 students (Jackson & Boutte, 2018; Tzou et al., 2021). It is important to mention that none of the studies reviewed addressed preparing PSTs for teaching EDIS lessons to special education students and emergent bilinguals. This finding is not in keeping with Project 2061, which advocates for Science for all Americans (American Association for the Advancement of Science [AAAS], 1994). These students are an important group based on the US statutes that provide guidance and directives on ensuring adequate learning standards for them (e.g., Individuals with Disabilities Education Act, 2004; Every Student Succeeds Act, 2015). It is incumbent on teacher preparation programs to incorporate instruction on creating EDIS lessons that are inclusive of special education students, minority students, and emergent bilinguals.

Similarly, examining PST beliefs about new teaching methods before interventions is important in shifting these beliefs toward utilizing these methods (Varma et al., 2009; Volkmann et al., 2005). Similar outcomes were observed in the reviewed studies that included this task in their intervention, like Hammack and Vo (2022) and Pleasants et al. (2022). The insights from both studies emphasize the significance of engaging PSTs in reflective practices, like the methodologies adopted by Antink-Meyer et al. (2023) and Menon and Azam (2021), in facilitating shifts in PSTs' conceptions about engineering. These reflections act as powerful catalysts, enabling PSTs to bridge gaps in their understanding, subsequently forming new visions about the role of engineering and its integration in science teaching. By reflecting on their experiences and pre-existing beliefs, PSTs have the opportunity to reassess and reshape their perspectives, drawing closer alignment with the objectives of engineering design integration.

These benefits highlight the importance of understanding PSTs' pre-existing beliefs and the sources from which they derive these beliefs. This understanding will help science teacher educators tailor interventions to address misconceptions effectively and shift PSTs’ beliefs toward those aligned with engineering design integration. The same applies to the task of providing PSTs with tools to evaluate EDIS instruction and its influence on student learning. Ensuring that this task is explicitly addressed in interventions can go a long way in ensuring PSTs do not feel ill-prepared for teaching EDIS lessons and can enhance their self-efficacy for engineering design integration in science teaching (Capobianco et al., 2022; Webb & LoFaro, 2020).

Implications for Teacher Preparation

The teacher preparation landscape is rapidly evolving, particularly in science and engineering education. With the recent shift towards EDIS instruction (NGSS Lead States, 2013), there is a growing emphasis on equipping teachers with the necessary knowledge and skills to integrate engineering design into science teaching. Multiple studies (e.g., Hammack & Vo, 2022; Nesmith & Cooper, 2021; Pleasants et al., 2020; Tank et al., 2020) underscore the necessity for teachers to develop an understanding of engineering design and how to integrate it into science teaching. The common observation is that PSTs often oversimplify concepts from science and engineering design. This oversimplification can result in their students having an incorrect understanding of the subject matter knowledge. Hence, it's vital for teacher preparation programs to stress the distinctions between these two fields while also highlighting their interconnectedness. The integration of specially designed experiences, such as hands-on interactions with the engineering design process, can increase teachers' confidence and abilities in this domain.

Another major implication is the need to delve deeper into the complexities of engineering design process, as seen in Wendell (2014) and Maiorca and Mohr-Schroeder (2020). PSTs need to be exposed to more open-ended engineering challenges, which underline the significance of refining problem scopes and gathering relevant information. These experiences should be coupled with the development of teamwork and communication skills, essential competencies in the 21st-century science classroom. Such teacher preparation is likely to equip teachers with skills for guiding students in tackling authentic and engaging engineering design problems, promoting a deeper understanding of the subject. An interesting perspective provided by Capobianco and Radloff (2022) and Capobianco et al. (2022) revolves around guiding preservice teachers through a diversified trajectory of practices, from adaptive approximations to utilizing delivery pedagogies. This multi-faceted approach to teacher preparation encourages the development of innovative teaching methods. Moreover, collaborating efforts, reflective practices, and hands-on activities are paramount in enhancing the pedagogical content knowledge related to EDIS teaching. Providing these experiences to PSTs throughout their preparation journey can lay a good foundation for their future teaching endeavors.

Likewise, as highlighted by Kim et al. (2019) and Yesilyurt et al. (2021), there is an imperative need to transcend traditional boundaries. Integrating engineering concepts and design skills within other disciplines, such as life sciences or mathematics, can provide a holistic teaching approach. This integration, however, necessitates overcoming various barriers, including resource limitations and the need for improved professional development. French and Burrows (2018) bring forth a unique implication, emphasizing the significance of preservice science teachers engaging in Authentic Science Inquiry (ASI). This approach fosters a deeper understanding of scientific concepts and nurtures skills like experimental design and peer communication. Furthermore, studies by Menon et al. (2023) and Ryu et al. (2019) highlight the importance of integrated STEM education, suggesting that partnerships between interdisciplinary faculty members and engagement with experienced teachers can be instrumental in enhancing teacher preparation. This collaboration can lead to significant positive shifts in teachers' self-efficacy and attitudes toward STEM teaching when coupled with opportunities for observation and hands-on practice.

An insightful observation from Menon and Azam (2021) is the significance of considering a teacher's past experiences in molding their approach to science teaching. This dynamic process of identity development, intertwined with field experiences and practical teaching, requires ongoing support, reinforcing the idea that teacher preparation is not a one-size-fits-all process, but a journey tailored to each individual. The findings of Antink-Meyer et al. (2023) underscore the need to innovate and adapt traditional methods. Traditional journaling, for instance, may not suffice in nurturing teachers' curiosity and wonder in the modern teaching landscape. Incorporating strategies that bridge conceptual learning with personal relevance can provide teachers with the tools to develop more engaging and effective teaching strategies.

Another implication is the obligation to improve PSTs’ content knowledge for engineering beyond the efforts shared in this review. In this review, all studies integrated engineering design coursework into their interventions. Despite the promising outcomes shared from these studies, the authors noted the difficulties and challenges PSTs faced when integrating engineering design into their science teaching. One possible way to address this issue is to include appropriate engineering coursework in teacher education content courses, too. For example, chemistry PSTs can have introductory chemical engineering classes included in their chemistry content course requirements. Similarly, biomedical and genetic engineering concepts can be included in biology courses for PSTs or civil and environmental engineering in earth sciences courses. This can provide the necessary engineering subject matter knowledge that studies show is inadequate among PSTs (Banilower et al., 2018; Pleasants et al., 2020). This can also improve PSTs' readiness to transfer some engineering design activities they were exposed to during their teacher preparation into EDIS lessons in schools.

An additional implication necessary for the long-term success of science teacher education that is related to engineering design and the NGSS is the need for in-service teacher training in engineering design integration. Studies show that in-service teachers say that engineering design professional development is most needed compared to other subjects (e.g., Haag & Megowan, 2015). Other studies also confirm that professional development can improve in-service teachers' efficacy and implementation of integrated engineering design in science classrooms (e.g., Guzey et al., 2014; Hammack et al., 2020). The effect of this on teacher preparation is that when PSTs are sent out for field experience in schools, they are more likely to be mentored by teachers who are receptive to teaching science using engineering design. This means there will be less pushback from mentor teachers as PSTs implement EDIS teaching in schools during field experiences.

Implications for Future Research.

The studies reviewed in this paper present insights and directions for improving teacher preparation through multiple research domains, such as science education, engineering design, instructional methods, and self-efficacy beliefs. From the analysis of these studies, certain implications for future research emerged, providing an understanding of what these findings collectively mean for the future of research in science teacher preparation. Several studies emphasized the importance of fostering PSTs' deeper understanding of engineering education and integrated STEM curricula (Hammack & Vo, 2022; Kim et al., 2019; Maiorca & Mohr-Schroeder, 2020). For example, Hammack and Vo (2022) highlighted the need to focus on problem scoping and design optimization, and Kim et al. (2019) called for a more profound exploration of classroom practices and PSTs' comprehension of integrated engineering design and science teaching methods.

A recurring theme across the reviewed studies is exploring and developing assessment tools, instructional strategies, and interventions to deepen PSTs' understanding of how to teach science using engineering design (Pleasants et al., 2020; Wendell, 2014; Capobianco & Radloff, 2022). Wendell (2014) urges the examination of various interventions, such as real-world design problems, to support PSTs' understanding of engineering design. Similarly, Pleasants et al. (2020) offer new ways to analyze and score teachers' perceptions of engineering and engineering design teaching, presenting opportunities for further exploration. Such shared emphasis on innovation and investigation indicates a collective push toward diversifying teaching methodologies and advocating for hands-on, practical approaches in teacher education programs. Several studies also focus on the efficacy of PSTs and the need to understand the influences that shape their confidence, beliefs, and abilities (Yesilyurt et al., 2021; Kaya et al., 2019; Perkins Coppola, 2019). These insights underscore the importance of creating supportive environments in teacher preparation programs that foster confidence and practical skills. As Menon et al. (2023) suggested, longitudinal studies on these areas would provide valuable insights into long-term development and sustained impact.

Other implications also emerged from some studies, indicating specific avenues for exploration. For instance, Capobianco et al. (2022) emphasized the longitudinal development and impact of integrating engineering practices into science teacher preparation programs. This focus on long-term effects and early career influences presents a unique perspective that could revolutionize how research into teacher preparation programs is structured and evaluated. Webb & LoFaro (2020) stand out for their focus on culturally responsive engineering education, addressing the need to support underrepresented students. This focus on diversity and inclusion has far-reaching implications, suggesting that more needs to be done to understand the influence of integrating culturally responsive methodologies and encouraging a broader and more equitable approach to K-12 science student learning outcomes in EDIS lessons. Another distinct study, Antink-Meyer et al. (2023), emphasizes curiosity journaling strategies and inquiry engagement, presenting a novel way of fostering motivation, interest, and identity among teachers. Such a unique focus adds a psychological dimension to research into teacher preparation that has the potential to encourage programs to cultivate intellectual curiosity as a vital aspect of effective teaching.

Finally, the studies reviewed underscore the importance of collaboration between educational institutions, teachers, schools, and industry in teacher preparation in engineering design, as Ryu et al. (2019) noted. This collaboration can lead to comprehensive models for partnerships, potentially transforming the quality of teacher preparation in engineering design and of K-12 engineering design integration. This highlights a systemic approach, indicating that the future of research in teacher preparation for teaching science through engineering design may lie not just in the refinement of individual programs but in a more interconnected, collaborative effort involving multiple stakeholders.

In conclusion, the reviewed studies present a multifaceted view of the outcomes, current challenges, and opportunities in research related to engineering design integration in teacher preparation. As shown in Table 1, there was significant variation in the intervention structures and learning tasks based on the review framework. Studies also provide insight into how these intervention structures and learning tasks affect PSTs learning about EDIS teaching and their potential to integrate engineering design into science instruction. They highlight common themes around enhancing K-12 science and engineering education, developing innovative instructional strategies, fostering teacher efficacy, and offering unique insights into areas such as culturally responsive teaching and curiosity-driven education. The synthesis of these studies calls for a holistic, innovative, and collaborative approach to teacher preparation in EDIS teaching, reflecting a dynamic and multifaceted vision for the future of science education. By embracing these findings, teacher preparation programs can prepare a new generation of science teachers who are better equipped, confident, and responsive to diverse students in science classrooms.

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Table 1
List of Studies Reviewed

Study	Purpose	Design, Participants, Data, & Analysis	Intervention structure	Presence of tasks for learning to teach EDIS lessons 1	2	3	4	5	Outcomes
Tank et al., 2020	To describe variations in implementing engineering design-based lesson after professional development (PD).	*Qualitative*: 20 elementary PSTs. Lesson plans, classroom artifacts, field observations – Case study, Open coding analysis	*Duration*: 16 weeks *Integrated Coursework*: PD experience within teacher preparation program; Hexbug challenge. *Field experience & mentoring*: Triad model with mentors & engineers		X		X	X	PSTs varied in integrating engineering design into classroom practice. Common characteristics included problem-solving, materials exploration, building, and testing. Study provided insight for supporting PSTs in implementing engineering.
Wendell, 2014	To understand PSTs' starting points for learning to teach engineering design through integrating engineering with children's literature & literacy skills.	*Qualitative*: 26 elementary PSTs. Video recording & transcripts – Discourse analysis	*Duration*: Not mentioned directly. Appears to be one semester. *Integrated coursework*: Elementary science teaching methods course; Literature-based design challenges. *Field experiences & mentoring*: None mentioned.	X	X		X		PSTs' attention to engineering design was relatively stable. Novice & expert engineers emphasized problem definition & information gathering. Implications: PSTs need opportunities to learn problem scoping.
Maiorca & Mohr-Schroeder, 2020	Elucidated how early-career PSTs developed integrated STEM lesson plans through engineering design approach.	*Qualitative*: 16 elementary PSTs. Lesson plans – Deductive content analysis	*Duration*: One week *Integrated coursework*: Elementary mathematics methods course; Model eliciting activities (MEAs). *Field experiences & mentoring*: facilitated middle school hands-on challenges & field trips.		X		X		PST struggled with integrating science into STEM lessons. Most PSTs successfully integrated engineering & mathematics. Lack of experience impacted the authenticity of engineering design problems. PSTs need more support in STEM education.
Capobianco & Radloff, 2022	Examined how PSTs integrate engineering design into science	*Qualitative*: 18 elementary PSTs. Self-interviews,	*Duration*: 16 weeks *Integrated coursework*: Elementary science methods	X	X	X	X		PSTs showed promising intentions for engineering design-based science teaching. Three trajectories

	teaching during a 16-week method course.	lesson plans, reflective narratives, & classroom observations – Deductive open coding analysis	course; engineering design tasks, lesson plan development. *Field experiences & mentoring*: About 4 – 5 class sessions.						of practice emerged: adaptive approximations, compartmentalizing practices, using delivery pedagogies. Variations in developmental trajectories were influenced by context & time.
Kim et al., 2019	Explored PSTs' understanding of engineering & its design process using Perkins's "knowledge as design" theory.	*Qualitative*: 31 secondary PSTs. Field notes, interviews, artifacts, reflective journals, & observation notes – Open coding & inductive analysis, constant comparative analysis.	*Duration*: Not mentioned directly. Appears to be one semester. *Integrated coursework*: Secondary science instructional methods course; Engineering design activities, comparing Engineering & Science. *Field experiences & mentoring*: Not mentioned.	X	X		X		PSTs who engaged in engineering design activities gained confidence in teaching engineering through hands-on activities. Engineering design enhanced PSTs' systematic thinking skills. Barriers include limited time, resources, & teacher preparation.
French & Burrows, 2018	Analyzed PSTs' proficiency in designing inquiry-based lessons before & after Methods course emphasizing authentic science inquiry.	*Qualitative*: 38 secondary PSTs. Lesson plans questionnaire with scenario responses – Content analysis using scoring.	*Duration*: Not mentioned directly. Appears to be one semester. *Integrated coursework*: Secondary science methods courses; Engineering design activities, computer programming, engineering content classes. *Field experiences & mentoring*: 16-week residency.		X		X	X	PSTs consistently included use of scientific instruments & group work in lesson plans. There's a gap in PSTs' backgrounds, emphasizing the need for undergraduate research projects. Most lessons focused on hands-on activities, but lacked comprehensive ASI components like developing testable questions.
Capobianco et al., 2022	Investigated how elementary PSTs develop understandings about engineering design-based science teaching.	*Qualitative*: 45 elementary PSTs. Self-interviews, Reflective narratives – Open coding & document analysis	*Duration*: 16 weeks. *Integrated coursework*: Elementary science methods course; Engineering design tasks, lesson plan development, engineering content classes. *Field experiences & mentoring*: 10 three-hour sessions.	X	X		X		PSTs developed engineering pedagogical content knowledge (PCK) through design experiences. Course facilitated shifts from learners to teachers of engineering design. Teacher educators should provide situated, social, & distributed instruction.
Carpenter et	Examined PSTs'	*Qualitative*:	*Duration*: 5 weeks.	X	X		X		PSTs' understanding of models in

al., 2019	comprehension of the practice of developing & using models in STEM education.	8 prospective teachers & 4 secondary PSTs. Interviews with PSTs & potential teachers, focus group interviews with mentor teachers – Thematic analysis.	*Integrated coursework*: No specific coursework reported; Scholarship based practicum experiences. *Field experiences & mentoring*: The Project-Based Engineering Academy (PBEA) & The Green STEM Academy (GSA).				science instruction varied. Prospective teachers had more varied understandings compared to PSTs. PSTs need exposure to engineering instruction to understand NGSS practices.
Menon & Azam, 2021	Explored the development of science teaching identity in two PSTs from the United States & Canada over time.	*Qualitative*: Two Elementary PSTs. Written science autobiographies, questionnaire, written reflections, classroom observations, & field-notes – Case study & content analysis.	*Duration*: One year. *Integrated coursework*: Science methods course; Engineering design integration, practice-based investigations, 5E instructional model, lesson plan development. *Field experiences & mentoring*: 45 minutes of science teaching, three times per semester.	X	X	X	Fresh experiences during teacher preparation courses affected teacher identity. Initial teacher identity shaped by prior science experiences. Field experiences shaped PSTs' science teacher identity. Teacher educators should consider past experiences & modeling effective pedagogies.
Ryu et al., 2019	To describe how STEM PSTs experienced teaching STEM through an integrated methods course.	*Qualitative*: Three secondary PSTs, two university bound PhD students, one prospective teacher in informal settings. 1 hour long semi-structured interviews, lesson plans, reflections, & a final paper – Grounded theory, open coding, axial coding, graphing, & tabulation.	*Duration*: Not mentioned directly. Appears to be one semester. *Integrated coursework*: Integrated STEM teaching methods course; Discipline-specific instructional approaches, engineering/technology design *Field experiences & mentoring*: One integrated STEM lesson taught in a partner school.	X	X	X	Participants used various approaches for integrated STEM lessons. Factors influencing lesson development: experiences, interests, disciplinary backgrounds, local contexts. Challenges in implementing integrated STEM education: school culture, limited STEM knowledge, absence of role models. Suggestions for successful STEM integration: establish partnerships, utilize online resources, use interdisciplinary examples, encourage reflection.
Estapa & Tank, 2017	Investigated how a PD program, centered on engineering design,	*Qualitative*: 10 elementary PSTs. Survey, lesson plans,	*Duration*: one-week PD, entire study – one semester. *Integrated coursework*:	X	X		Engineering design process facilitated successful integrated STEM activities. Teacher training

	influenced triads' integration of STEM concepts in elementary classrooms.	field-notes, online post-lesson survey – Content analysis	Summer PD experience; Hexbug engineering design challenge, engineering content, integration of engineering design into STEM. *Field experiences & mentoring*: 16-week student teaching placement.						should bridge learning from planning to enacting. Engaging PSTs as learners before implementation improves enactment. Sustaining integration of STEM concepts is challenging for PSTs.
Pleasants et al., 2019	Investigated elementary PSTs' perspectives on student learning outcomes during engineering design lessons over a semester.	*Qualitative*: No specific mention of number of elementary PSTs but 56 interviews were obtained from PSTs. Semi-structured interviews – Content analysis.	*Duration*: 16 weeks *Integrated coursework*: Science teaching methods course; Engineering design activity from Engineering Is Elementary (EIE). Comparison of science & engineering. *Field experiences & mentoring*: 16-week student teaching placement.		X		X		PSTs prioritized learning in terms of engineering practices & the Nature of Engineering (NOE) like cooperating teachers. The influence of professional development workshops & engineer's presence in the classroom may have shaped PSTs' emphasis on the NOE. Many PSTs focused on the EDP in their teaching, aligning with common curricular materials but potentially oversimplifying the complexity of engineering practice.
Hammack & Vo, 2022	Explored PSTs' understanding of engineering using the Draw-An-Engineering-Teacher-Test (DAETT) & case-based reasoning.	<u>*Mixed Methods*</u> 34 elementary PSTs. *Quantitative*: Draw-An-Engineering-Teacher-Test (DAETT) – Mann-Whitney U test *Qualitative*: Discussion board posts & responses - Open coding analysis.	*Duration*: 16 weeks *Integrated Coursework*: Elementary science methods course; Case-based approach; readings & online discussions *Field experience & mentoring*: No mention	X	X				PSTs struggled to discern teaching science & engineering. PSTs valued building in engineering & emphasized the need for problem-solving. PSTs benefited from engineering experiences & discussions.
Pleasants et al., 2020	Assessed the impact of teaming PSTs & elementary teachers with engineering graduate students on	<u>*Mixed Methods*</u> 80 elementary PSTs. *Quantitative*: Draw-An-Engineer-Test (DAET) – Chi-	*Duration*: One semester *Integrated Coursework*: Two-day professional development (PD) workshop; Modeling of engineering design, nature of	X	X		X	X	Professional development positively impacted PSTs' conceptions of engineering. PSTs' representations became more specific & accurate but differed

	the teachers' understanding of engineering.	Squared tests of association *Qualitative*: DAET descriptive codes - Open coding analysis.	engineering, & how engineers use science. *Field experience & mentoring*: Triad model with mentors & engineers						from engineers. PSTs' understanding of engineering may have differed from those of expert engineers.
Yesilyurt et al., 2021	Examined how an engineering unit in an elementary science teaching methods course impacts PSTs' engineering teaching self-efficacy belief.	*Mixed Methods* 84 elementary PSTs. *Quantitative*: Engineering Teaching Efficacy Belief Instrument (ETEBI) – Paired samples t-test. *Qualitative*: PSTs' Reflections about engineering – Thematic analysis	*Duration*: One semester *Integrated coursework*: Science teaching methods course; Engineering design challenges, nature of engineering, demonstrated engineering classes. *Field experiences & mentoring*: None mentioned.	X	X		X	X	Engaging in hands-on activities and explicit instruction improved engineering teaching efficacy. Cognitive content and cognitive pedagogical mastery were important efficacy sources. Future engineering interventions should emphasize design activities and nature of engineering.
Menon et al., 2023	Investigated how a redesigned STEM block impacted PSTs' conceptions & self-efficacy regarding integrated STEM instruction.	*Mixed Methods* 132 elementary PSTs. *Quantitative*: Self-efficacy for Teaching Integrated STEM (SETIS) instrument. – Paired t tests & Cohen's D effect sizes. *Qualitative*: STEM identity letters, STEM growth reflections, STEM session observations – Content analysis	*Duration*: 15-16 weeks. *Integrated coursework*: Newly redesigned elementary STEM course; Discipline-specific instructional approaches for STEM, science & engineering practices, engineering design, 5E lesson planning, mathematical modeling, & robotics/coding. *Field experiences & mentoring*: 2-day practicum per week.	X	X		X		PSTs showed significant positive gains in integrated STEM self-efficacy. Integrated STEM discourse across courses positively impacted PSTs' understanding of engineering design integration. STEM educators should realign programs for explicit integrated STEM instruction.
Webb & LoFaro, 2020	Examined how a STEAM methods course influenced PSTs' self-efficacy in teaching engineering practices.	*Convergent mixed methods* 14 elementary PSTs. *Quantitative*: Teacher Sense of Self-Efficacy Scale	*Duration*: 15 weeks. *Integrated coursework*: Science, technology, engineering, arts, & mathematics (STEAM) methods course; Engineering		X	X	X	X	STEAM methods course increased PSTs' engineering self-efficacy significantly. The course design with longer duration had a greater impact. Culturally responsive teaching

		(TSES) – Two-tailed t-tests. *Qualitative*: Focus group interviews – Deductive open coding analysis.	design integrated into STEM, language arts integration, simulated modeling of engineering design challenges. *Field experiences & mentoring*: None mentioned.						practices influenced PSTs' cognitive pedagogical mastery. Longitudinal studies needed to observe self-efficacy patterns and challenges.
Antink-Meyer et al., 2023	Explored how PSTs' scientific curiosity influenced their confidence & its potential implications for novel science teaching practices.	<u>*Mixed Methods*</u> 29 elementary PSTs. *Quantitative*: Survey for teaching confidence – Chi-square test of association. *Qualitative*: Curiosity journal entries – Open coding analysis.	*Duration*: 16 weeks *Integrated coursework*: Science teaching methods course; Nature of science & engineering; NGSS science & engineering practices. *Field experiences & mentoring*: None mentioned.		X		X	X	Curiosity expressed was related to some topical areas of confidence. PSTs' curiosity about content may influence self-efficacy for teaching. Need to explore differences in curiosity between teachers and students in teaching and learning.
Nesmith & Cooper, 2021	Assessed the impact of an engineering unit on PSTs' engineering teaching self-efficacy beliefs & perspectives towards engineering implementation.	*Quantitative*: 27 elementary PSTs. Teaching engineering Self-efficacy Scale (TESS) – Wilcoxon signed rank test.	*Duration*: 13 weeks *Integrated Coursework*: Science methods course; Engineering design task, readings, discussions. *Field experience & mentoring*: Field-based practicum course	X	X		X	X	The engineering unit positively impacted PST's understanding and self-efficacy. PST recognized engineering design as a natural integrator with STEM. The unit enhanced PST's understanding of the 5E inquiry process.
Kaya et al., 2019	Explored integrating 3D printing into elementary science teaching methods & its impact on PSTs' engineering teaching efficacy beliefs.	*Quantitative*: 20 elementary PSTs. Engineering Teaching Efficacy Belief Instrument (ETEBI) – Paired samples t-test.	*Duration*: 2 weeks. *Integrated coursework*: Elementary science teaching methods course; Engineering design tasks (3D printing). *Field experiences & mentoring*: None mentioned.	X	X		X	X	PST Personal Engineering Teaching Efficacy (PETE) scores significantly increased after engineering instruction. PSTs' understanding of engineering improved through 3D printing experiences. Preservice teachers benefit from teaching engineering design.
Perkins Coppola, 2019	Explored how modifying a science methods course influenced PSTs' self-efficacy for teaching engineering.	*Quantitative*: 124 elementary PSTs. Teaching Engineering Self-Efficacy Scale (TESS) – Two-tailed	*Duration*: 14 weeks. *Integrated coursework*: Science teaching methods course; Engineering mini units (EMU), lesson plan development. *Field experiences &*	X	X		X	X	Integration of EMUs improved PSTs' self-efficacy in teaching engineering. Engineering Pedagogical Content Knowledge Self-Efficacy had the largest gain. Further research is needed on mindset and long-term outcomes.

		paired sample t-tests.	*mentoring*: Two days per week for 11 weeks in an elementary school.						
Mumba et al., 2023	Evaluated the representation of science & engineering practices in EDIS instructional units created by PSTs.	*Quantitative*: 51 secondary PSTs. Engineering design integrated science (EDIS) units – Scoring of anchor phrases & words.	*Duration*: Not mentioned directly. Appears to be one academic year. *Integrated coursework*: Science teaching methods course *Field experiences & mentoring*: One semester of student teaching.	X		X	X		PSTs successfully included engineering practices across science disciplines. Explicit instructional approach to engineering design is recommended in teacher education. Overall, findings contribute to better teaching & learning of science & engineering design.

Note: EDIS = Engineering design integrated science; PD= Professional development; 1 = Analyzing Beliefs and Forming New Visions of Teaching Science Through Engineering Design; 2 = Developing Science and Engineering Subject Matter and Pedagogical Knowledge and the Demands of Engineering Design; 3 = Forming an Understanding of Diverse Learners in Science and Engineering Design Instruction; 4 = Growing a Beginning Repertoire for Engineering Integrated Science Instruction; = Identifying Tools to Study Engineering Design Integrated Science Instruction and Its Impact on Student Learning

Manuscript 2

Developing Secondary Pre-Service Science Teachers’ Self-Efficacy for Teaching Engineering

Abstract

This study investigated the changes in and sustainability of self-efficacy of secondary pre-service science teachers for teaching engineering design before and after engineering design integrated science (EDIS) instruction in a science methods course and after teaching EDIS units in schools. After learning about engineering design and how to integrate it into science instruction in science methods course pre-service teachers created and taught EDIS units in schools during student teaching. In the EDIS units, pre-service teachers taught both engineering design and science concepts. Participants completed Teaching Engineering Self-Efficacy Scale (TESS) survey before and after the EDIS instruction in the science methods course, and after teaching EDIS units in schools. The results show that the pre-service teachers' self-efficacy for teaching engineering increased from pre-instruction on EDIS instruction in a science methods course to post-implementation of EDIS units in schools. The linear growth model analysis also revealed that time had a significant positive effect on pre-service teachers' development of self-efficacy for teaching engineering design.

In the United States, science education framework (National Research Council [NRC], 2012) and the Next Generation Science Standards (NGSS; NGSS Lead States, 2013) call for the integration of engineering design into science instruction. The reasons for integrating engineering in science classrooms are to improve science instruction through the design of prototypes (Rockland et al., 2010); improve student learning in science due to engineering's application-focused nature (Berland et al., 2014); and generate interest in students for engineering (Guzey et al., 2016). However, the call for integrating engineering in science instruction has caused several challenges to teachers (Aranda et al., 2020; Bamberger & Cahill, 2013). For example, studies show that many teachers have limited engineering knowledge and report feeling unprepared to teach engineering (Carr et al., 2012; Hammack & Ivey, 2017). This challenge has been attributed to teachers' lack of formal preparation in engineering (Radloff & Capobianco, 2021; Banilower et al.,2018). Banilower et al. reported that only 13% of high school teachers, 10% of middle school science teachers, and 3% of elementary school teachers had college coursework in engineering.

Similarly, Fantz et al. (2011) reported that very few teacher education programs prepare pre-service science teachers (PSTs) in engineering design and how to integrate it into science teaching. Science teachers' lack of formal preparation in engineering is problematic for the effective implementation of the current science education framework (NRC, 2012) and NGSS engineering practices (NGSS Lead States, 2013) in schools. Science teachers who are deficient in engineering are less prepared to teach it in science classrooms (Leonard & Derry, 2011). Likewise, science teachers with low self-efficacy for engineering instruction are not likely to teach it and subsequently fail to develop engineering skills among students (Nesmith & Cooper, 2019).

These challenges suggest that the effective integration of engineering in science classrooms will largely depend on the preparation science teachers receive in engineering (Capobianco & Radloff, 2022; Banilower et al., 2018) and their self-efficacy for teaching it (Perkins Coppola, 2019). Therefore, science teachers need preparation in engineering for them to effectively teach it in schools (Capobianco & Radloff, 2022; Carr & Strobel, 2011). Additionally, research on science teachers' preparation in engineering is still nascent. Most studies on engineering in teacher education have focused on elementary PSTs (e.g., Nesmith & Cooper, 2019; Perkins Coppola, 2019). Little is known about secondary PSTs' self-efficacy for teaching engineering in science classrooms. As such, researchers have called for more research on engineering in secondary science teacher education (Chandler et al., 2011; Daugherty & Custer, 2012). For example, Daugherty and Custer suggested research on how science teachers develop engineering knowledge and confidence for teaching it.

To start addressing these challenges, we have integrated engineering into our science teacher education program in order to help secondary PSTs develop an understanding of engineering design, learn how to integrate it into science teaching, and increase their confidence in teaching it. In this paper, therefore, we describe PSTs' self-efficacy for teaching engineering design before and after instruction on engineering design integrated science (EDIS) in a science methods course and after teaching EDIS units in schools.

In this study, we assumed that assessing PSTs' self-efficacy for teaching engineering will serve as a measure of their confidence in teaching it in science classrooms. This study also adds to the literature on engineering in science teacher education by using a Linear Growth Model (LGM, Hox et al., 2017) to assess changes in PSTs' self-efficacy for teaching engineering throughout the instruction period.

The study sought to answer the following questions: (1) To what extent does participation in the instruction on EDIS teaching in a science methods course and teaching EDIS units in schools impact secondary PSTs' self-efficacy for teaching engineering? (2) To what extent does PSTs' self-efficacy for teaching engineering change throughout the EDIS intervention when controlling for gender and teaching subject areas?

Rationale and Significance of Study

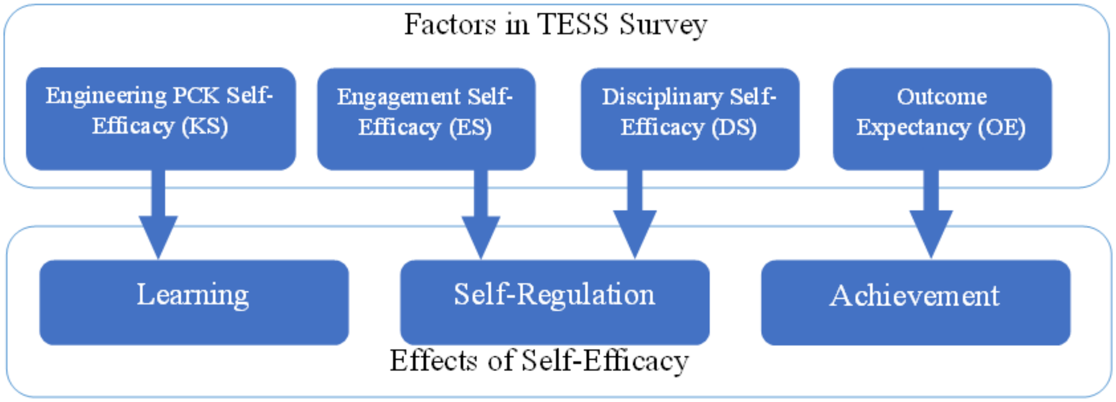
This study is important for the following reasons: first, this study goes beyond previous studies on engineering in teacher education by examining secondary PSTs' self-efficacy for teaching engineering design in science classrooms after learning about engineering in a science methods course, and after teaching EDIS units in schools. Second, the findings of this study have implications for the teaching and learning of engineering in teacher education and schools. For example, science teacher educators may use the EDIS instruction described herein in developing science methods courses and professional development programs for preparing teachers in engineering. Similarly, science curriculum designers may use the EDIS instruction described herein and results as guides in developing engineering design integrated science units and activities for science classrooms. School administrators would become aware of how they can support their science teachers to effectively teach engineering in science classrooms. Additionally, science education researchers may use the findings of this study as a starting point for further research on engineering in science teacher education.

Theoretical Framework

Self-efficacy is described as an individual's perception of their ability to learn or perform a task (Bandura, 1977). According to Schunk and Pajares (2009), self-efficacy has four primary effects, motivation, learning, self-regulation, and achievement. Persons with high levels of self-efficacy are generally theorized to be highly motivated to attain their ambitions regardless of actual or perceived hindrances they anticipate or face. As learners, they are expected to be higher achieving when compared to persons with low self-efficacy. The main elements in the EDIS instruction in the science methods course in this study are aligned with three of the four self-efficacy effects: *learning, self-regulation, and achievement*. For example, during the EDIS instruction, learning was prioritized by focusing on understanding the NGSS, the engineering design process, and how to integrate it into science teaching. Participants also learned about the similarities and differences between the scientific inquiry and engineering design process. The EDIS instruction addressed the engagement component of the self-regulation effect by having PSTs participate in EDIS activities and EDIS units development. An additional self-regulation effect occurred when the PSTs taught their EDIS units in schools during student teaching. The achievement effect is primarily represented in the implementation phase, where the PSTs assessed students' learning in the EDIS units they taught in schools. However, student learning outcomes have been presented elsewhere (see Authors, 2019).

Figure 1

Alignment of Self-efficacy Effects with TESS Instrument



Likewise, the Teaching Engineering Self-Efficacy Survey (TESS; Yoon et al., 2014) used in this study to measure PSTs' self-efficacy for teaching engineering is aligned with the four effects of self-efficacy (Schunk & Pajares, 2009). Figure 1 below shows how the factors in the TESS survey are aligned with the effects of self-efficacy as hypothesized by Schunk and Pajares (2009).

As shown in Figure 1, the items for the *Engineering PCK Self-efficacy* (KS) factor measure learning. Teachers with high KS can be theorized to have a more substantial knowledge base for engineering design. According to Schunk and Ertmer (2000), self-regulation influences one's knowledge and performance through individually inspired and specifically designed acts and affects. This effect is theorized to be associated with *Engagement Self-efficacy* (ES) and *Disciplinary Self-efficacy* (DS) factors of the TESS instrument (Perry & Steck, 2015), while *Outcome Expectancy* (OE) factor is thought to be aligned mostly with achievement (Shell et al., 1989).

Literature Review

Current science education reforms describe engineering design is described as an iterative process that provides the platform for applying scientific knowledge and students' engagement in engineering (NRC, 2012). Three core ideas of engineering design are: the definition of problems to be addressed, ideating solutions, and optimization of selected design solutions (NGSS Lead States, 2013).

Although science education reforms require science teachers to incorporate engineering design into their science teaching, most teachers lack engineering knowledge and self-efficacy for teaching it. For example, Hammack and Ivey (2017) investigated elementary teachers' engineering self-efficacy and engineering teaching efficacy. They found that teachers had low engineering self-efficacy for teaching engineering to their students. Dare et al. (2014) also reported that physical science teachers had challenges in integrating engineering into their lessons in physics lessons. Similarly, Nadelson et al. (2016) found that elementary teachers conveyed inadequate representations of engineering practices and design processes. These deficits in engineering knowledge among teachers reveal the need for interventions to improve their pedagogical content knowledge for engineering in science classrooms. As such, some studies have reported on the effect of professional development on teachers' engineering knowledge and self-efficacy for teaching engineering. For example, Rich et al. (2017) provided a year-long professional development on engineering and computing to elementary teachers. Participant teachers improved their self-efficacy for teaching engineering after the professional development. The improvement in teachers' self-efficacy was attributed to engineering activities in the professional development.

Similarly, Nesmith and Cooper (2021) provided an integrated engineering design unit in a science methods course for elementary PSTs. After learning about engineering design in the science methods course, PSTs implemented engineering design lessons in schools. The results showed that PSTs increased their engineering knowledge and self-efficacy for teaching engineering in elementary classrooms. In a related study, Webb and LoFaro (2020) integrated a science, technology, engineering, arts, and mathematics (STEAM) unit into a teaching methods course for PSTs. After the intervention, participant PSTs developed positive perceptions of engineering and expressed confidence in teaching engineering practices. Kelley et al. (2020) also sought to find out how three years of professional development in engineering impacted a group of science and engineering technology teachers' self-efficacy for teaching science, technology, engineering, and mathematics (STEM) lessons. They found that teachers demonstrated a high level of self-efficacy in teaching STEM lessons. Likewise, Kaya et al.'s (2019) reported that after incorporating 3D printing knowledge into an engineering design challenge, PSTs increased their engineering teaching efficacy beliefs.

Not all studies have reported improvement in teachers' self-efficacy for teaching engineering after participation in interventions on engineering. For example, Perkins Coppola (2019) integrated engineering design in a science methods course for elementary PSTs and analyzed how it affected the their self-efficacy for teaching engineering. Although PSTs' engineering pedagogical content knowledge, engagement self-efficacy, and disciplinary self-efficacy significantly improved after the intervention, their outcome expectancy did not significantly improve. Likewise, Yesilyurt et al. (2019) did not find significant improvement in teachers' expectations for engineering teaching outcomes after implementing an intervention on engineering among pre-service teachers. These findings emphasize the need to consider contextual factors when trying to improve teachers' self-efficacy for teaching engineering. For example, Tschannen-Moran and Hoy (2007) reported that contextual factors, such as the available teaching resources and interpersonal support, were more salient in the self-efficacy beliefs of novice teachers than they were for experienced teachers.

Few studies have looked at secondary PSTs' improvement in their knowledge and teaching of engineering-related instruction. French and Burrows (2018) examined PSTs lesson plan scenarios before and after intervention in two secondary science methods courses. The courses provided opportunities for the PSTs to incorporate engineering design into their lesson plans. Their findings suggest that the PSTs were proficient in ensuring student collaboration, data collection, data analysis, and the use of scientific instruments. However, PSTs needed more support in creating plans that inspired students to think of testable questions, reassess methodology, engage in peer review, and communicate their findings to a scientific audience. Kim et al. (2019) aimed to advance professional knowledge concerning the engineering and engineering design process knowledge of PSTs. Their findings suggest that such theoretical agreement exists as participants with a limited understanding of engineering design exhibited creative ways of applying their scientific knowledge to solve engineering problems. This study highlights the learning potential for pre-service teachers when they are fully immersed in instruction that seeks to improve the integration of engineering into science instruction. These studies provide an invaluable understanding of how secondary science PSTs engage with the process of improving their science instruction through teaching engineering.

It is evident from the literature that research on engineering in science teacher education is nascent. Interventions in engineering design have led to improvement in teachers' self-efficacy for teaching engineering. However, most studies on teachers' self-efficacy for teaching engineering are on elementary pre-service teachers. There is a paucity of research on secondary PSTs' self-efficacy for teaching engineering. As such, little is known about PSTs' self-efficacy in teaching engineering. Therefore, the current study extends this line of research by investigating the changes in and sustainability of self-efficacy of secondary PSTs for teaching engineering design before and after engineering design integrated science (EDIS) instruction in a science methods course and after teaching EDIS units in schools.

Study Context and EDIS Instruction

This study was conducted in a one-year graduate secondary science teacher education program that leads to a master's in teaching degree and a teaching license. In addition to other education courses, PSTs take two science methods courses, one in the fall semester and the other in the spring semester. The EDIS instruction was done in a science methods course in the fall semester for six weeks. PSTs received additional instruction and support on EDIS teaching in a seminar course in the spring semester. Before learning about engineering design and how to integrate it into science teaching in the science methods course in the fall semester, PSTs learned how to teach science using guided instructional practice, inquiry, stations, and problem-based learning. The objectives for the EDIS instruction were for PSTs to learn how to read NGSS; understand and apply engineering design process; understand and apply science and engineering practices; understand similarities and differences between the engineering design process and scientific inquiry process; create a collection of EDIS teaching resources; develop EDIS units; and teach EDIS units in schools during student teaching.

The EDIS instruction in a science methods course was carried out by two engineering professors and two science education professors. In the first week of the instruction, the PSTs were introduced to the NGSS and how to read them. Also covered were the three NGSS dimensions: Disciplinary core ideas, science and engineering practices, and Crosscutting concepts.

The second week centered on the nature of engineering and engineering teaching kits (ETKs; Richards et al., 2007). This session builds upon the second part of the first week, where the instructor led an in-depth exposition on the engineering discipline, starting with the variety of divisions within engineering. Next, the concept and role of design, not just in engineering but in society at large, was discussed comprehensively. These discussions were done to aid in shifting how the PSTs viewed engineering design’s role in learning and modern society. Next, the PSTs were introduced to the ETKs, which are hands-activities on Engineering design challenges designed to inspire critical evaluations of the intricacies of engineering from the teacher and student perspectives. PSTs were challenged to design a load-bearing solar-powered car using their understanding of energy conversion, solar power, electricity, force, and mechanics (Richards et al., 2007). PSTs defined the challenge, redefined the problem, developed knowledge, ideated solutions, built prototypes, tested, and evaluated the prototypes, and redesigned them. Then, they presented their cars, the design process, the energy transformation processes, and their reflections on the design process to their peers and instructors. We also discussed the modifications PSTs would make to the activity for middle and high school classrooms.

In week three, the focus was on comparing the scientific inquiry process with the engineering design process and the integration of engineering design into science teaching. This session aimed to ensure the PSTs reflected on the natures of both disciplines and, despite the significant overlap, developed an intuitive appreciation of how they differ. An important example of this is that although both engineering design and the scientific inquiry process require research and data analysis, the aims of the research are different. For science, this is often in search of new knowledge, while for engineering, a solution to a human or societal need is usually the primary objective. Next, the PSTs were introduced to the science and engineering integration continuum model (Authors, 2017). This activity was aimed at stressing to the PSTs the importance of balance in their EDIS units by ensuring that the students did and learned both science and engineering.

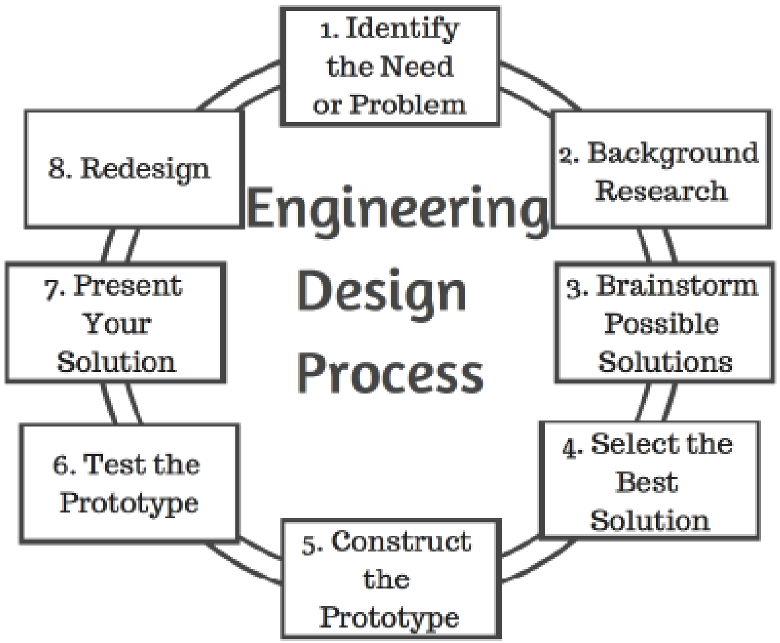
In the fourth week, PSTs were introduced to engineering resources (e.g., teachengineering.org) and tasked to create a collection of EDIS activities relevant to their teaching subject areas. This activity was designed to prepare PSTs to adapt EDIS instructional materials developed by others. For each resource, PSTs were asked to (1) provide a brief description of how the resource would be used to teach science concepts and engineering design to students; (2) identify engineering design skills, science and engineering practices, disciplinary core ideas and crosscutting concepts the resource is addressing; and (3) describe modification(s) they would make to the resource to effectively address engineering design and science concepts in their classrooms. In the fifth and sixth weeks of the instruction, the focus was on EDIS unit development. The pre-service teachers were given a unit plan template to develop their EDIS units. Each pre-service teacher was required to create one EDIS unit (see example EDIS unit as Appendix 1). Then, the pre-service teachers presented their EDIS units to instructors and peers and received feedback. Then, they revised their EDIS units based on the feedback and submitted them for grading.

EDIS Units Implementation in Schools

Each cohort of PSTs taught EDIS units in middle and secondary schools in the subsequent spring semester during student teaching. This was the requirement for the seminar course. Each EDIS unit followed the engineering design process steps depicted in Figure 2 below. These steps include identifying the problem, undertaking background research, thinking up potential solutions, selecting the best solution, constructing a prototype, testing the prototype, presenting the solution, and potentially redesigning. However, the science topics and content covered in the units varied. Pre-service teachers started EDIS instruction in science classrooms with the introduction of the engineering design process through an interactive presentation (see Figure 2).

Figure 2

Engineering Design Process Model



After the formal presentation of the engineering design process, students were presented with engineering design challenges. Students were required to find a solution to the challenges by working their way through the engineering design process, depicted in Figure 2. Students worked in groups throughout the EDIS units to complete their engineering design challenges. After explaining the design process and the design challenges, the PSTs transitioned into facilitators while the students developed their solutions to the design challenges. Students were required to create prototypes, test them, and present them to peers and teachers. Then, students redesigned their prototypes based on feedback from peers and teachers.

Methods

Design

A one-group pretest-posttest experimental design (Frey, 2018) was employed. Each cohort of the PSTs completed the TESS survey (see Appendix 2) before and after EDIS instruction in the science methods course and after teaching EDIS units in schools.

Participants

The participants were 40 PSTs enrolled in a science teacher education program at a research university between 2016 to 2021. There were 26 females and 14 males. Most participants were white (32), and only eight were from underrepresented populations. There were 26 PSTs in biology, 6 in earth sciences, 5 in engineering, 2 in physics, and 1 in chemistry.

Data Instrument and Collection

Data was collected using the *Teaching Engineering Self-efficacy Scale* (TESS; Yoon et al., 2014). This survey has four factors which are engineering pedagogical content knowledge self-efficacy (KS), engineering engagement self-efficacy (ES), engineering disciplinary self-efficacy (DS), and outcome expectancy (OE). The TESS survey has 23 items on a 6-Likert Scale from Strongly disagree (coded 1) to Strongly agree (coded 6). The nine items in the KS factor measure the teachers' confidence in their ability to teach engineering, to facilitate student learning based on engineering knowledge applicable to a teaching context. The four items in the ES factor measure the teachers' confidence in their potential to engage students in engineering classes. The five items in the DS factor measure the teachers' confidence in their capacity to manage a variety of student behaviors during engineering projects. The five items in the OE factor measure the teachers' personal confidence in the impact of instruction on student engineering learning. The instrument was administered to PSTs before and after the instruction in a science methods course and after teaching EDIS units in schools.

Data Analysis

Data analysis started with computing descriptive statistics and reliabilities (Cronbach's α). Then, Two-tailed paired sample *t*-tests were performed for the overall Teaching engineering

Self-efficacy (TES) construct and for each of the four factors to determine if there is a significant difference between the pre-posttest means. The *t*-test pairs performed were for the pre-test and post-instruction, the post-instruction and post-implementation of EDIS units in schools, and the pre-test and post-implementation of EDIS units in schools. Standardized effect sizes were also evaluated based on the *t*-test pairs, and effect sizes from 0.2 – 0.49 were classified as small, 0.5 – 0.79 as medium, and > 0.8 as large (Cohen, 1988).

For the second research question, a two-level linear growth model (LGM) was used to evaluate the change in self-efficacy for teaching engineering over the three time periods. The primary reason for this analysis method is the data's time-nested nature and the superiority of multi-level growth models over ordinary least squares methods (Singer & Willett, 2003). The time points in the data were coded 0 through 2. Although it is common to include a random effect for time in growth models (i.e., the assumption that all participants do not change at the same rate; Palardy (2010)) with these data, including a random effect term for time produced singular fit errors during analysis. Hence, we did not estimate a random effect for time in our models. This is likely due to the small sample size. Below is the model equation used in the analysis.

$$Yti = \gamma 00 + \gamma 10 Timeti + \gamma 01 Male0i + \gamma 02 Phy0i + \gamma 03 Env0i + \gamma 04 Time * Phy0i + \gamma 05 Time * Env0i + u0i + eti$$

Y_{ti} represents the model's outcome: TES, KS, ES, DS, and OE. $Male_{0i}$ represents student sex, and $Time_{ti}$ is the variable for time. Concerning teaching subjects, three dummy variables were created for life sciences, physical sciences (Phy_{0i}), and environmental sciences (Env_{0i}). Life sciences were used as the reference variable and excluded from the models. Before LGM analysis, the linearity of the outcome variables was assessed against time. If a non-linear relationship were to be observed, then a non-linear term would be added to the models above. Analysis was done using the R statistical software (R Core Team., 2021) with the lme4 package (Bates et al., 2015). The deviance values were used to assess the models based on the $\chi 2$ likelihood ratio test to establish the best fit. The best-fitting model should have the lowest deviance value and ideally be statistically different from the other models. All models were estimated using maximum likelihood with an unstructured variance/covariance matrix. Neither sex nor teaching subject have random effects as they do not change in the study. Assumptions of residual normality, homoscedasticity, and independence were analyzed to confirm that no glaring violations were observed.

Results

Pre–Post EDIS Instruction in Science Methods Course

Table 1 below shows the results of the descriptive statistics, internal consistency analysis, *t*-test mean difference comparisons, and standardized effect sizes by factors. The reliability of the obtained data based on Cronbach's α for the TES construct was 0.92 for both pre-test and post-instruction time points. Therefore, the instrument was reliable, and the data was analyzed to report PSTs' self-efficacy for teaching engineering.

Table 1

Pre – Post-instruction in the Science Methods Course

Factor	Pre-Mean (SD)	Post-Mean (SD)	Pre α	Post α	*t*	*p*	Cohen's *d*
KS	3.81 (1.11)	5.29 (0.57)	0.96	0.87	8.11	< 0.001	1.68
ES	4.95 (0.79)	5.61 (0.54)	0.82	0.86	6.56	< 0.001	0.99
DS	4.02 (0.95)	4.70 (0.77)	0.93	0.92	4.91	< 0.001	0.78
OE	3.99 (0.83)	4.59 (0.73)	0.85	0.83	3.92	< 0.001	0.76
TES	4.12 (0.70)	5.09 (0.51)	0.92	0.92	7.80	< 0.001	1.57

N = 40; KS- Engineering PCK Self-efficacy; ES-Engagement Self-efficacy; DS- Disciplinary Self-efficacy; OE-Expectancy (OE).

As shown in Table 1, the pre-post mean differences are statistically significant, with p-values less than 0.001. The findings indicate that the PSTs in this study improved across all the factors of self-efficacy for teaching engineering after EDIS instruction in the science methods course. This is confirmed by the overall TES construct results showing a *t*-value of 7.8 and a p-value less than 0.001. The standardized effect sizes (Cohen's d) echo these results with medium to high effect sizes across all factors. These standardized effect sizes indicate that the EDIS instruction was very effective at increasing PSTs' self-efficacy for teaching engineering across all factors measured. We can also compare the effect sizes, and from the results in table 1 above, it is apparent that the EDIS instruction had the largest effect on the KS factor (teachers' confidence in their ability to teach engineering to facilitate student learning). On the other hand, the OE factor (the teachers' personal confidence in the impact of instruction on student engineering learning) received the least impact.

Post-Instruction in Science Methods Course–Post-Implementation in Schools

Table 2 shows the results for post-EDIS instruction in science methods course and post-EDIS unit implementation in schools. Cronbach's α values for the factors in the survey fell above the threshold for exploratory research (0.70). The instrument was reliable, and the data was analyzed to report PSTs' self-efficacy for teaching engineering.

Table 2

Post-instruction (P-In) – Post-implementation (P-Im)

Factor	P-In Mean (SD)	P-Im-Mean (SD)	P-In α	P-Im α	*t*	*p*	Cohen's *d*
KS	5.29 (0.57)	5.25 (0.52)	0.87	0.87	0.58	0.57	0.07
ES	5.61 (0.54)	5.36 (0.55)	0.86	0.72	3.25	0.002	0.46
DS	4.70 (0.77)	4.97 (0.79)	0.92	0.95	2.26	0.03	0.35
OE	4.59 (0.73)	4.42 (0.87)	0.83	0.91	1.64	0.11	0.21
TES	5.09 (0.51)	5.03 (0.54)	0.92	0.94	0.87	0.39	0.10

N = 40; KS- Engineering PCK Self-efficacy; ES-Engagement Self-efficacy; DS- Disciplinary Self-efficacy; OE-Expectancy (OE).

As shown in Table 2, there was no statistical difference between the TES mean differences. PSTs maintained their self-efficacy level for teaching engineering they developed after the EDIS instruction in a science methods course. However, the mean differences in two factors (ES and DS) were statistically significant when comparing post-EDIS instruction to post-implementation of EDIS units in schools. This result indicates that across all factors assessed, there was little change in PSTs' self-efficacy for teaching engineering between the post-instruction and post-implementation of EDIS in schools. Cohen's d results reflect this, with all standardized effect sizes falling under the small category.

Pre-EDIS instruction–post-Implementation

Table 3 below shows the pre-EDIS instruction in the methods course and post-implementation of EDIS units in schools data analysis. The internal consistency findings are identical to the results explained in the previous two sections. The mean differences were statistically significant for the TES and across all the four factors. Between the pre-test and post-implementation data, the KS factor has the largest t-value of 8.74 and the most considerable Cohen's d effect size of 1.67, categorized as a large effect size.

Table 3

Pre-instruction (P-In) – Post- Implementation (P-Im)

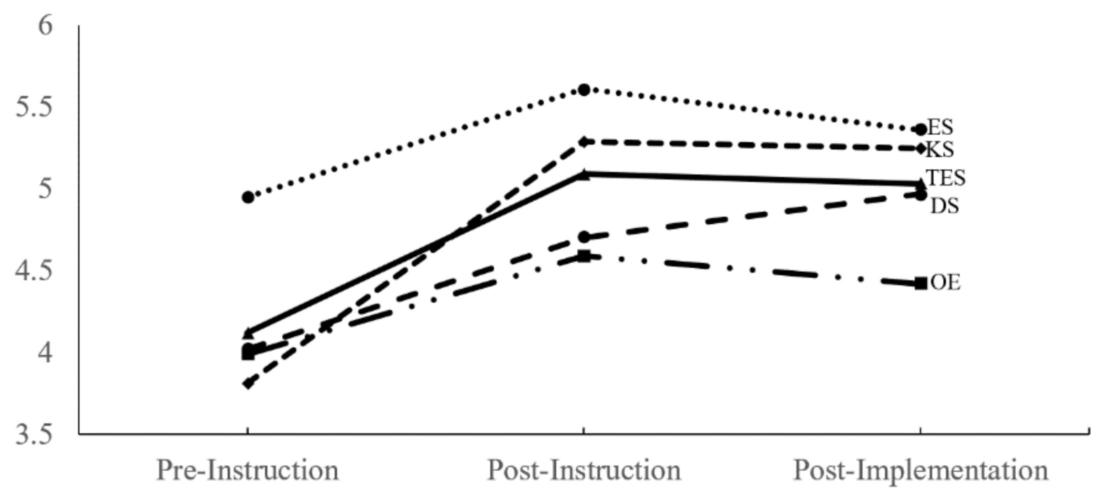
Factor	P-In-Mean (SD)	P-Im-Mean (SD)	P-In α	P-Im α	*t*	*p*	Cohen's *d*
KS	3.81 (1.11)	5.25 (0.52)	0.96	0.87	8.74	< 0.001	1.67
ES	4.95 (0.79)	5.36 (0.55)	0.82	0.72	3.43	0.001	0.61
DS	4.02 (0.95)	4.97 (0.79)	0.93	0.95	6.93	< 0.001	1.08
OE	3.99 (0.83)	4.42 (0.87)	0.85	0.91	2.77	0.009	0.50
TES	4.12 (0.70)	5.03 (0.54)	0.92	0.94	7.91	< 0.001	1.45

N = 40; KS- Engineering PCK Self-efficacy; ES-Engagement Self-efficacy; DS- Disciplinary Self-efficacy; OE-Expectancy (OE).

The OE factor has the lowest t-value of 2.77 and a commensurate lowest Cohen's d effect size of 0.5, just big enough to be classified as a medium effect size based on the classification criteria outlined earlier in this paper. These findings indicate that across the study, the PSTs were able to develop and sustain their self-efficacies for teaching engineering in science classrooms.

Figure 3 below provides a graphical representation of how the factor averages changed across the data collection periods. The line graph shows that, on average, for all factors measured, the PSTs improved their self-efficacy for teaching engineering after EDIS instruction in the science methods course. This improvement is most discernable with the KS factor, which had the lowest average score at pre-EDIS instruction. From post-EDIS instruction in science methods course to post-implementation of EDIS units in schools, the graph shows slight decreases for most of the factors except for the DS factor. This indicates that the PSTs maintained their self-efficacy for teaching engineering they developed in EDIS instruction in science methods course even after they taught EDIS units in schools.

Figure 3
Change in TESS Factor Averages Over Data Collection Period



Linear Growth Model Results

At the beginning of the study (i.e., time = 0), the average self-efficacy for teaching engineering for PSTs in this study, irrespective of all covariates (unconditional model), was 4.75 ($p < 0.001$) (Table 4), which was statistically significant. The four factors' averages were also statistically significant ($p < 0.001$) and ranged from 4.33 (OE) to 5.31 (ES). This indicates that the PSTs began the EDIS instruction with some confidence in teaching engineering. The intra-class correlations (ICCs) for all outcomes are listed in the note section of the estimates table (Table 4). For the overall TES construct, the ICC indicates that 5.9% of the variance in the outcome is between PSTs. The ICC for the KS factor was undetermined due to a near-zero intercept variance, thus indicating undetectable variance in this outcome between PSTs at the first data collection time point. The ICCs for ES, DS, and OE factors indicated that 30.2%, 32.2%, and 34% of the total variance was between PSTs, respectively.

Table 4

Linear Growth Model (LGM) Estimates Table for all TESS Factors

Fixed Effects	TES	KS	ES	DS	OE
Intercept (UM)	4.75*(0.07)	4.78*(0.12)	5.31*(0.08)	4.56*(0.11)	4.33*(0.10)
Intercept (FM)	4.29*(0.09)	4.06*(0.12)	5.10*(0.10)	4.09*(0.13)	4.12*(0.12)
Time	0.46*(0.06)	0.72*(0.09)	0.21*(0.06)	0.47*(0.07)	0.21*(0.07)
Random Intercept	0.10	0.11	0.16	0.35	0.26
Residual	0.30	0.62	0.28	0.35	0.42
Δ-2LL[b]	223.36*	299.63*	228.56*	269.94*	278.43*

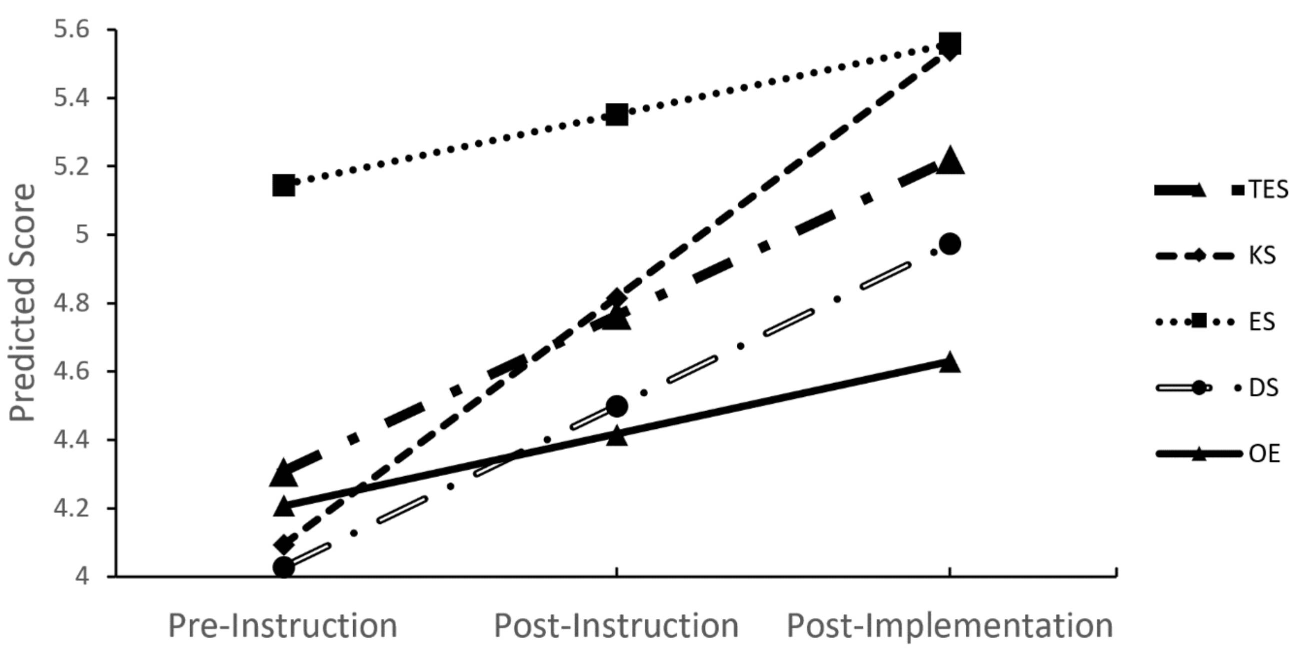
*p<0.05 two-tailed test, UM = Unconditional Model, FM = Final Model,
[b]Change in the -2LL contrasts final model to the unconditional model,
ICC: TES = 0.059, KS = N/A, ES = 0.302, DS = 0.322, OE = 0.340.
KS-Engineering PCK Self-efficacy; ES-Engagement Self-efficacy; DS-Disciplinary Self-efficacy; OE-Outcome Expectancy

LGM analysis results for four nested models were obtained; the unconditional model (no predictors included), model with time as only predictor, model with teaching subjects and sex included, and model with cross level interaction between time and teaching subjects included. Of the four models specified, the time only model was the only model to show deviance-based (Δ-2LL) statistical significance. Consequently, only this model was used for further inference and analysis. For the overarching TES construct, and all four factors (Table 4), on average, moving from one-time point to the next (pre-instruction – post-instruction or post-instruction – post-implementation) increased TES by a score of 0.46 ($p < 0.001$), which is statistically significant.

Concerning the KS, ES, DS, and OE factors, time had a significant effect with coefficients of 0.72 ($p = < 0.001$), 0.21 ($p = 0.001$), 0.47 ($p < 0.001$), and 0.21 ($p = 0.004$), respectively.

The effect of time on the outcome variables is visualized in Figure 4 below. The figure below shows a comparison of the effect of the EDIS instruction and implementation on all four factors and the TES construct. From the figure, it is easy to see that the outcome most influenced in this study is the KS factor. Starting out with the second lowest average score, this factor ended with the joint highest. This is corroborated by KS having the largest coefficient for time (0.72) among all the factors measured. This result also indicates that the self-efficacy dimension the participants improved the most on was their learning in comparison to self-regulation (ES and DS) and their perception of their student's achievement based on their engineering teaching (OE).

Figure 4
Change in TESS Factors Predicted Scores Over Data Collection Period



Discussion

Results show that the Teaching Engineering Self-efficacy (TES) construct and all four self-efficacy factors measured significantly increased from pre-test to post-instruction in the science methods course. For the post-EDIS instruction to post-implementation of EDIS units in schools, only the mean difference of two factors were statistically significant. However, from pre-EDIS instruction in science methods course to post-implementation of EDIS units in schools, all four factors and the TES construct were statistically significant. Linear growth model results revealed time had significant positive effect on PSTs' development of self-efficacy for teaching engineering.

These results indicated that the pre-service teachers' self-efficacy for teaching engineering increased significantly from before EDIS instruction to after the implementation of EDIS units in schools. The KS factor (engineering pedagogical content knowledge self-efficacy) had the largest standardized effect size of 1.68 from the pre to post-EDIS instruction. This period represented the time when the pre-service science teachers were being exposed for the first time to the concept of engineering design and how to integrate it into science teaching. This finding is supported by Perkins Coppola (2019), who also found the KS factor to have the most considerable effect size after instruction. However, the KS effect size between post-EDIS instruction and post-implementation (0.07) was the lowest within this period. This outcome suggests that the pre-service teachers maintained their engineering pedagogical content knowledge self-efficacy they developed in the science methods course. On the other hand, the KS of the pre-service teachers across the entire instruction and implementation shows that there was a significant increase. These results indicate that the pre-service teachers improved their engineering pedagogical content knowledge self-efficacy (KS) level from after being exposed to EDIS teaching during this study.

Within the pre-test and post-EDIS instruction periods, the pre-service teachers developed considerably in their abilities to self-regulate themselves and their environment for maximum performance. This is evident in the ES (Engagement Self-efficacy) and DS (Disciplinary Self-efficacy) results that show statistically significant increases and medium to large effect sizes (0.99 and 0.78, respectively). Similar to the findings in other studies (Nesmith & Cooper, 2021), the ES factor had the most significant pre-test mean (4.95). According to Hammack and Ivey (2017), this could be because actively engaging teachers is a part of teaching, that brings satisfaction to them.

On the other hand, after teaching EDIS units in schools the ES factor dropped by an average of 0.25 points, and DS increased by an average of 0.27 points. This drop can be attributed to some factors science teachers experienced when implementing EDIS units in schools. Implementing engineering design in the classroom for the first time has significant challenges for experienced teachers (Nadelson et al., 2016), which are heightened for novice teachers (French & Burrows, 2018). It is plausible that practical experience in teaching science using engineering design can cause a reduction in the PSTs' ES scores. This result is in keeping with the literature that says issues with student engagement can negatively influence a novice teacher's teaching self-efficacy (Tschannen-Moran & Hoy, 2007).

Despite these significant effects on PSTs' self-efficacy for teaching engineering, it is essential to note that the standardized effect sizes for the factors measured. Across the whole study, the PSTs' self-regulation increased significantly, with a medium effect size for ES (0.61) and a large effect size for DS (1.08). These results indicate that the PSTs improved their self-efficacy for adapting their affective state and external environments for optimal performance in the classroom. A probable distal effect of this is an improvement in their abilities to persevere while using EDIS instruction as a conduit for science teaching despite the likely challenges they might face (Nadelson et al., 2016).

In this study, the PSTs' OE factor changed significantly after the EDIS instruction in the science methods course but not after EDIS units implementation in schools. The results indicate that after the instruction in the science methods course, the PSTs assessed themselves as having a higher perception of the influence of their teaching on student learning. This perception appeared to decrease, albeit insignificantly, after the implementation of EDIS units in schools. Nesmith and Cooper (2021) reported the same finding. However, Perkins Coppola (2019) reported non-significant mean differences in OE before and after the instruction. As such, researchers have argued that to improve OE studies should provide PSTs with various mastery experiences of engineering design that reinforce their self-efficacy for teaching engineering (Rich et al., 2017). The evidence from this study shows that an integrated approach to engineering design provides the necessary opportunity to increase PSTs' teaching engineering self-efficacy. The impact of the integrated approach to teaching engineering was significant on the self-efficacy of the PSTs across the entire study, with a Cohen's d coefficient of 1.45. Despite this result, the insignificant impact after classroom implementation calls for more research on this topic. This reduction in the averages of KS, ES, and OE factors after implementation lends credence to the argument that novice teachers need more support during their first years of teaching engineering in science classrooms.

This study also used LGM to analyze the changes in PSTs' teaching engineering self-efficacy. The findings show that PSTs have variable levels of self-efficacy for teaching engineering. The four primary sources of self-efficacy are mastery experience, vicarious experience, psychological state, and verbal persuasion (Bandura, 1977). Each PST's sources of self-efficacy in engineering design are unique, leading to differing levels of personal judgment of their ability to teach science using engineering design concepts. Addressing the second question, the learning effect of self-efficacy for teaching engineering in science classrooms can be seen to increase at a statistically significant rate across all three time periods. This provides evidence that as the PSTs moved from one point to another, their knowledge of engineering design improved significantly. Based on the results, the self-regulation effect, which is aligned with the ES and DS factors, appears to increase significantly for both ES and DS factors. Despite evidence that self-regulatory teacher skills such as classroom management are primary skills many PSTs struggle with (Hudson et al., 2019), difficulties with maintaining appropriate classroom discipline are among the primary reasons novice teachers give for leaving teacher education programs (Theelen et al., 2019). Outcome expectancy changed significantly over time despite other studies showing that OE is a problematic factor to improve in PSTs (Hammack & Ivey, 2017).

Implications and Conclusions

These findings have implications for teacher preparation and teaching of engineering in science classrooms. Many teachers are not prepared to integrate engineering design into science instruction. Our results and those reported in previous studies show that focused instruction on engineering in teacher education leads to improved teachers' self-efficacy for teaching engineering. However, PSTs' low self-efficacy for teaching engineering design, reported in our pre-instruction results and in previous studies, should be a call to action in science teacher education. Science teacher education programs should refocus their science methods courses to explicitly address engineering design to ensure that PSTs are adequately prepared to teach science and engineering design as prescribed in the NGSS. Based on the results in this study and those reported in previous studies, we believe an implicit instructional approach to engineering design in science teacher education is likely to limit the opportunity for teachers to develop more self-efficacy for engineering in science classrooms.

Although the findings in this study cannot be generalized due to the small number of participants, our findings suggest the evidence to support the need for professional development on engineering design for secondary PSTs to develop their self-efficacy for teaching engineering in science classrooms.

We also suggest areas for future research on engineering design in science teacher education. First, the researchers should investigate the relationship between PSTs' understanding of engineering design and their teachers self-efficacy for teaching engineering in schools. Second, there is a need to investigate the association between teachers' self-efficacy in teaching engineering and student learning in science classrooms. These studies would provide evidence on whether teachers' self-efficacy is related to their understanding of engineering, EDIS instruction practice, and students' learning in science and engineering design.

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Appendix 1: Example EDIS Unit

Engineering Design Integrated Science Unit Plan

Subject: Honors Biology
Topic: Cell Transport Across the Cell Membrane
Grade Level: 9-10
Duration: 3.5 – 90 Minute Blocks (315 minutes)

Background

German physiologist Rudolph Virchow first theorized cellular pathology--disease at the cellular level--in the 1850s. Today, new treatments for many disorders are a direct result of understanding a disease process at the cellular level. Abnormalities in organelles such as the cell membrane, can cause whole-body symptoms.

Cystic fibrosis was first described in medical journals in the late 1930's as a defect in the pathways leading from certain glands. This caused an array of problems including thick mucus in the lungs and frequent infection; a clogged pancreas, preventing digestive juices from reaching the intestines; and salty sweat. Cystic fibrosis is just one example of how genetic abnormality causes symptoms felt at a whole-body level.

The plasma membrane plays an integral role in maintaining homeostasis by controlling what comes into and out of the cell. We have discussed how small defects that result in some loss of function of the plasma membrane can result in major disorders, such as Duchenne Muscular Dystrophy and Cystic Fibrosis.

Some small, non-polar molecules are able to cross the plasma membrane along the concentration gradient directly through the phospholipid bilayer. Other smaller charged molecules, like water and charged ions, are able to cross the membrane via channel proteins through the process of facilitated diffusion. Some substrates need to be pumped across the membrane against the concentration gradient (or may be too large to cross the membrane) and require an energy input and/or the help of carrier proteins to cross the membrane via active transport.

In this design challenge, you will be acting as biomedical engineers who are responsible for designing a cell membrane that allows different substrates to cross it via a variety of "transport and channel proteins" to replace the faulty membranes in cystic fibrosis patients.

Your model should demonstrate the phospholipid bilayer and include representations of: Hydrophobic tails, Hydrophilic heads, Transport proteins, and Channel proteins and cholesterol that will be able to transmit four materials that represent different types of substrates that would need to enter/exit a cell. These substances may enter via simple diffusion, facilitated diffusion or active transport. Your prototype must represent each of these processes in the sense of whether or not extra energy (ATP) is needed.

PART I: Learning Objectives

Essential Questions:

How does the cell membrane help maintain homeostasis inside of the cell?

What are the steps of the Engineering Design Process?

State Standards:

----Listed here---

Next Generation Science Standards:

- **HS-LS1-2.** Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms.
- **HS - ETS1-1**. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.
- **HS - ETS1-2.** Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.
- **HS - ETS1-3**. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.

UKD's

Understand

- There are multiple forms of transport across a cell's membrane that help to maintain homeostasis.
- The Engineering Design process

Know

- The fluid mosaic model of a membrane emphasizes the arrangement and function of a bilayer of phospholipids, transport proteins, and cholesterol.
- Homeostasis of a cell is maintained by the plasma membrane comprised of a variety of organic molecules. The membrane controls the movement of material in and out of the cell, communication between cells, and the recognition of cells to facilitate multiple metabolic functions.
- Diffusion occurs in cells when substances (oxygen, carbon dioxide, salts, sugars, amino acids) that are dissolved in water move from an area of higher concentration to an area of lower concentration.
- Facilitated diffusion occurs in cells when larger substances are moved from an area of higher concentration to an area of lower concentration with the assistance of a carrier protein without the use of energy.
- Osmosis refers to the movement of water molecules through a semi- permeable membrane from an area of greater water concentration or pressure (lower solute concentration) to an area of lesser water concentration or pressure (higher solute concentration).
- Active transport refers to the movement of solid or liquid particles into and out of a cell with an input of energy.
- Genetic predisposition towards diseases impacts human health. Awareness of genetic predisposition allows individuals to make lifestyle changes that can enhance quality of life.
- Engineering design is an iterative process

Do

- Explain engineering design process
- apply the engineering design process.
- Identify the different parts of a phospholipid bilayer.
- Define and provide examples of osmosis, diffusion, and active transport.
- Model a semi-permeable membrane.
- Differentiate between passive and active transport, including examples of each.
- Design and build a semi-functional model of the phospholipid bilayer.
- Model how a concentration gradient influences the transport of materials across a membrane.

PART II: Materials/Resources (for 5 sections – 125 students - ~40 groups)

- Styrofoam balls – 36, 1.5in in diameter
- Scotch tape – 4 rolls
- Duct tape - 1 roll (60 meters)
- Cotton balls 200
- Toothpicks - 500
- Drinking Straws - 200
- Coffee Stirrers – 500
- Rubber Band - 500
- Paper Clips - 300
- Craft Foam – 50 sheets (5.5in x 8.5 in)
- Yarn – 397 yards
- Cheese cloth – 2 packages (36in x 6yd)
- Pipe cleaners - 100
- Aluminum Foil – 200 square feet
- Play-doh – 20, 3oz containers
- Q-tips – 1,0000

PART III: Engineering Design Overview

Design Process	Guiding Principles	Project Description:
Problem Definition Clarification/ Formulation	- Students should ideally identify users and needs. - Challenge should be relevant to students' lives - Offer multiple solutions so there is no one right answer - Students define specifications and constraints	• *Students will design a model of a cell membrane to help them further understand the components of the membrane as well as the different methods of transport across the membrane.* • *Students will take on the role of a biomedical engineer tasked with designing a functioning membrane for patients with cell membrane malfunctioning disorders such a cystic fibrosis and Duchenne Muscular Dystrophy.* • *They will need to pitch their prototype to the "board of a hospital (I.e. the teacher and their classmates)"*
Develop Knowledge Student-centered research or investigation into targeted concepts	Student-centered approach to background concepts, aligned with learning objectives -Offer multiple ways to give feedback on student ideas	• *Student's will investigate the parts of the cell membrane as well as the processes of diffusion and active transport of substances across the membrane.* • *Students will be prompted to think about the multiple components of the cell membrane including: hydrophobic tails, hydrophilic heads, transport proteins, channel proteins and cholesterol.*
Generate Ideas Students generate multiple solutions to problems	- Guide students to develop multiple solutions -Guide students to develop rationales for each solution -Pick and justify optimal design	• *Student's will sketch a design individually and then again collaboratively and plan out what materials they want to use based on the materials they are presented with.* • *Students will be prompted to justify each solution and then pick one design to model.*

Represent ideas/ develop prototype	- Explore different ideas through multiple representations (sketching, modeling, prototypes)	• *Student's will create a sketch and outline their budget as a group for the materials they want to choose.* • *They will only be able to build/test once or twice.* • *They will be allowed to re-evaluate their material usage if they'd like at any time during the building process. They will only need to worry about the cost of their final design and will be able to swap materials in and out as needed during the building and optimizing phases.*
Test and Evaluate Design Test prototype's ability to meet project goals	-Develop criteria for design evaluation, or have given criteria -Create tests to learn how prototypes behave and to optimize performance -Solicit feedback from others about design	• *Student's will present their prototypes and describe each of the required parts and the types of transport they are involved in. Students will be given a group grade on this as a part of their final grade along with their analysis worksheet.* • *They will test the functionality of their prototype by massing the sand and water before and after travelling through the membrane to determine the percentage of the substrate that was able to successfully cross the membrane. They will also be judged on whether or not their protein channels were able to be reset and reused.*
Revise Design Use evaluation and feedback to revise	-Guide students to use evaluation and feedback to revise design -Guide students to reflect on design and give justifications of revisions	• *Students will discuss how they could potentially revise designs based on their test results, feedback from other students and teachers, and observations of their classmate's designs. They won't actually carry out this phase and will instead reflect in writing in step eight on their engineering design packet*
Reflection and Extension	- Support reflection on design process - Check how well solution meets project criteria -Guide students to apply content in new context	• *Students will be reflecting on the entire engineering design process and their understanding of the cell membrane structure and function in their engineering design packets/worksheets.* • *Guided class discussion to reflect on design process after they've tested their models. They will discuss further why understanding cell membrane and its transport processes are important for real world applications of science.*

PART IV: Daily Unit Overview

Day 1: 90 Minutes (I split this day into 2 half days)

Learning Objectives:

Understand

- There are multiple forms of transport across a cell's membrane that help to maintain homeostasis.
- The Engineering Design process

Know

- The fluid mosaic model of a membrane emphasizes the arrangement and function of a bilayer of phospholipids, transport proteins, and cholesterol.
- Homeostasis of a cell is maintained by the plasma membrane comprised of a variety of organic molecules. The membrane controls the movement of material in and out of the cell, communication between cells, and the recognition of cells to facilitate multiple metabolic functions.
- Diffusion occurs in cells when substances (oxygen, carbon dioxide, salts, sugars, amino acids) that are dissolved in water move from an area of higher concentration to an area of lower concentration.
- Facilitated diffusion occurs in cells when larger substances are moved from an area of higher concentration to an area of lower concentration with the assistance of a carrier protein without the use of energy.
- Osmosis refers to the movement of water molecules through a semi- permeable membrane from an area of greater water concentration or pressure (lower solute concentration) to an area of lesser water concentration or pressure (higher solute concentration).
- Active transport refers to the movement of solid or liquid particles into and out of a cell with an input of energy.
- Genetic predisposition towards diseases impacts human health. Awareness of genetic predisposition allows individuals to make lifestyle changes that can enhance quality of life.

Do

- Identify the different parts of a phospholipid bilayer
- Define osmosis, diffusion, active transport
- Define semi-permeable membrane
- Define/identify examples of diffusion
- Define/identify examples of active transport

Materials/Resources Needed and Preparation Plans:

Lesson Segment & Time Est.	Materials	Instructional Sequence	Teacher/Student Actions
Introduction (10 minutes)	• Printed pre-assessments	• **Pre-Assessment**: Students will be given an eleven question pre assessment on Engineering Design and Cell Membrane and transport	Teacher: • Hand out pre-assessment • Collect pre-assessment Students: • Take pre-assessment
Body (70 minutes)	• PowerPoint • Guided Notes • Engineering Design Packets	• Introduce the engineering design cycle and relate it to the scientific method • Discuss the work of biomedical engineers. • Introduce a few diseases that are caused by a malfunctioning plasma membrane. • Introduce phospholipid bilayer components. • Teach diffusion and active transport • Introduce engineering design challenge and have them read through the introduction page and the rubric.	Teacher: • Hand out notes packet • Facilitate the presentation. • Question students to get them actively engaged in the presentation. • Introduce Engineering Design Challenge • Present the materials to the students that they will be able to use when building their model Students: • Follow along and participate in presentation. • Take notes on engineering design and cell membrane • Read through their engineering design packets • Look at materials
Closure	Venn-Diagram	• **Assessment with partners:** Venn diagram (3 part) comparing and	Teacher:

(10 minutes)	handout	contrasting simple diffusion, facilitated diffusion, and active transport • Assign Steps 1 & 2 on engineering design workbook for homework.	• Hand out Venn diagram • Go over Venn diagram with students and make sure they have all necessary information • Assign homework Students: • Work with partner on filling in the Venn diagram • Complete homework for next class

Day 2: 90 Minutes

Learning Objectives:

Understand

- There are multiple forms of transport across a cell's membrane that help to maintain homeostasis.
- The Engineering Design process

Know

- The fluid mosaic model of a membrane emphasizes the arrangement and function of a bilayer of phospholipids, transport proteins, and cholesterol.
- Homeostasis of a cell is maintained by the plasma membrane comprised of a variety of organic molecules. The membrane controls the movement of material in and out of the cell, communication between cells, and the recognition of cells to facilitate multiple metabolic functions.
- Diffusion occurs in cells when substances (oxygen, carbon dioxide, salts, sugars, amino acids) that are dissolved in water move from an area of higher concentration to an area of lower concentration.
- Facilitated diffusion occurs in cells when larger substances are moved from an area of higher concentration to an area of lower concentration with the assistance of a carrier protein without the use of energy.
- Osmosis refers to the movement of water molecules through a semi- permeable membrane from an area of greater water concentration or pressure (lower solute concentration) to an area of lesser water concentration or pressure (higher solute concentration).
- Active transport refers to the movement of solid or liquid particles into and out of a cell with an input of energy.

- Genetic predisposition towards diseases impacts human health. Awareness of genetic predisposition allows individuals to make lifestyle changes that can enhance quality of life.

Do

- apply the engineering design process.
- Identify the different parts of a phospholipid bilayer.
- Define and provide examples of osmosis, diffusion, and active transport.
- Model a semi-permeable membrane.
- Differentiate between passive and active transport, including examples of each.
- Design and build a semi-functional model of the phospholipid bilayer.
- Model how a concentration gradient influences the transport of materials across a membrane.

Materials/Resources Needed and Preparation Plans:

Lesson Segment & Time Est.	Materials	Instructional Sequence	Teacher/Student Actions
Introduction (10 minutes)	Formative assessment on half sheet of paper	• Formative assessment to be done on a half sheet of paper. 1. Differentiate between diffusion and facilitated diffusion. Give examples of molecules that experience each process. **2.** Define active transport and give an example of a substance that experiences this. **3.** Discuss how diffusion and active transport are different. Why is it necessary for a cell or organism to have	Teacher: • Hand out assessment • Go over answers with students while they self-grade. • Collect assessment Students: • Answer assessment questions • Grade their own papers.

		both?	

Body
 	
(70 minutes)
	• Engineering Design Packets
	• Styrofoam balls
	• Tape
	Cotton balls
	• Toothpicks
	• Drinking Straw
	• Coffee Stirrers
	• Rubber Band
	• Paper clips
	• Craft Foam
	• String
	• Cheese cloth
	• Pipe cleaner
	• Aluminum Foil
	• Play-doh
	• Q-tips
	• Sand
	• Water
	• Marbles
	• Pom-Poms
		• Refresh the students on what their design challenge is and remind them that they should have done steps 1-2 on their design worksheet for homework.
		• Assign groups with 3 students in each group
		• Begin at part 3 of their engineering design packet and work through the rest with their group.
		  • In groups they should compare ideas and pick the one they think is best (or combine them).
		  • In their groups, students should build their model of the cell membrane. They will need to include definitions as well as labels of each (see Appendix D - analysis questions)
		    • Their model will have to allow specific molecules to go through it (items that will represent water, carbon dioxide, oxygen, glucose, sodium, etc.)
		    • When they are completed these will be tested to see if they work (this
			Teacher:
			
			• Refresh students on their design task and the different steps of engineering design.
			• Remind students that where it says "Teacher Approval" they must check in with the teacher before moving on.
			• Assign activity groups of three (create beforehand)
			• Facilitate group's in going through the steps of the engineering design cycle.
			• Sign off on sections.
			
			Students
			
			• Re-read the first part of their engineering design worksheet and refresh themselves on what the problem and constraints are.
			• Get with assigned groups and begin working through steps 3-8 on their engineering design packet.
			• Get teacher approval in the appropriate sections before moving on to the next step

		most likely won't happen until next class).	
Closure (5 minutes)		• Depending on where students are at we will clean up and the teacher should re-iterate the design challenge and what is expected of the students.	Teacher • Facilitate cleaning up and re-iterate expectations for the group's models and presentations. • Let the students know that they will have half of next class to finish up their prototypes and then they will be presenting Students: • Clean up • Review expectations for the project

Day 3: 90 Minutes
Learning Objectives:
Understand

- There are multiple forms of transport across a cell's membrane that help to maintain homeostasis.
- The Engineering Design process

Know

- The fluid mosaic model of a membrane emphasizes the arrangement and function of a bilayer of phospholipids, transport proteins, and cholesterol.
- Homeostasis of a cell is maintained by the plasma membrane comprised of a variety of organic molecules. The membrane controls the movement of material in and out of the cell, communication between cells, and the recognition of cells to facilitate multiple metabolic functions.
- Diffusion occurs in cells when substances (oxygen, carbon dioxide, salts, sugars, amino acids) that are dissolved in water move from an area of higher concentration to an area of lower concentration.
- Facilitated diffusion occurs in cells when larger substances are moved from an area of higher concentration to an area of lower concentration with the assistance of a carrier protein without the use of energy.
- Osmosis refers to the movement of water molecules through a semi- permeable membrane from an area of greater water concentration or pressure (lower solute concentration) to an area of lesser water concentration or pressure (higher solute concentration).
- Active transport refers to the movement of solid or liquid particles into and out of a cell with an input of energy.
- Genetic predisposition towards diseases impacts human health. Awareness of genetic predisposition allows individuals to make lifestyle changes that can enhance quality of life.

Do

- apply the engineering design process.
- Identify the different parts of a phospholipid bilayer.
- Define and provide examples of osmosis, diffusion, and active transport.
- Model a semi-permeable membrane.
- Differentiate between passive and active transport, including examples of each.
- Design and build a semi-functional model of the phospholipid bilayer.
- Model how a concentration gradient influences the transport of materials across a membrane.

Materials/Resources Needed and Preparation Plans:

Lesson Segment & Time Est.	Materials	Instructional Sequence	Teacher/Student Actions
Introduction (5 minutes)		• Refresh the students on what their design challenge is.	Teacher: • Refresh students on what their design challenge is • Answer any questions • Give students instructions that they need to finish their designs in 20-30 minutes and then they will be presenting their prototypes. Students: • Ask any questions they may still have about the assignment

Body
 	
(80 minutes)
	• Engineering Design Packets
	• Styrofoam balls
	• Tape
	Cotton balls
	• Toothpicks
	• Drinking Straw
	• Coffee Stirrers
	• Rubber Band
	• Paper clips
	• Craft Foam
	• String
	• Cheese cloth
		• Have students finish their prototypes for around 25-35 minutes.
		• Groups will then present their prototypes and describe each of the required aspects as well as the function they are serving
		  • Hydrophobic tails
		  • Hydrophilic heads
		  • Transport proteins
		  • Channel proteins
		  • Cholesterol
		  • Simple diffusion
		  • Facilitated diffusion
			Teacher:
			• Circulate giving feedback to groups about their prototypes.
			• Question groups to be sure they understand the structure and functions of the cell membrane
			• Facilitate presentations
			• Fill out a rubric for each group as they present
			
			Students:
			• Continue to finish prototype.
			• If they finish they may begin analysis questions.
			• Students should present with their groups
			• Students should sit quietly while other groups are

	• Pipe cleaner • Aluminum Foil • Play-doh • Q-tips • Sand • Water • Marbles • Pom-Poms	• Active transport • Each group will be given a group evaluation	presenting • Students may give feedback to other groups if they wish
Closure (10 minutes)		• The students should reflect on their designs as well as their classmate's designs and complete part 8, redesign, in the engineering design packet. Students should talk about how they could have made their model better and whether or not their model met all the requirements. • Students will fill out a quick group evaluation form to give us feedback on how they felt the work was distributed throughout their group members).	Teacher: • Wrap up group presentations • Pass out group evaluation forms Students: • Finish part 8 in their engineering design packet • Complete group evaluation form.

Day 4: 45 Minutes
Learning Objectives:
Understand

- There are multiple forms of transport across a cell's membrane that help to maintain homeostasis.
- The Engineering Design process

Know

- The fluid mosaic model of a membrane emphasizes the arrangement and function of a bilayer of phospholipids, transport proteins, and cholesterol.
- Homeostasis of a cell is maintained by the plasma membrane comprised of a variety of organic molecules. The membrane controls the movement of material in and out of the cell, communication between cells, and the recognition of cells to facilitate multiple metabolic functions.
- Diffusion occurs in cells when substances (oxygen, carbon dioxide, salts, sugars, amino acids) that are dissolved in water move from an area of higher concentration to an area of lower concentration.
- Facilitated diffusion occurs in cells when larger substances are moved from an area of higher concentration to an area of lower concentration with the assistance of a carrier protein without the use of energy.
- Osmosis refers to the movement of water molecules through a semi- permeable membrane from an area of greater water concentration or pressure (lower solute concentration) to an area of lesser water concentration or pressure (higher solute concentration).
- Active transport refers to the movement of solid or liquid particles into and out of a cell with an input of energy.
- Genetic predisposition towards diseases impacts human health. Awareness of genetic predisposition allows individuals to make lifestyle changes that can enhance quality of life.

Do

- apply the engineering design process.
- Identify the different parts of a phospholipid bilayer.
- Define and provide examples of osmosis, diffusion, and active transport.
- Model a semi-permeable membrane.
- Differentiate between passive and active transport, including examples of each.
- Design and build a semi-functional model of the phospholipid bilayer.
- Model how a concentration gradient influences the transport of materials across a membrane.

Materials/Resources Needed and Preparation Plans:

Lesson Segment & Time Est.	Materials	Instructional Sequence	Teacher/Student Actions
Introduction (10 minutes)		• Review as a class up on the white board what the structure of a cell membrane consists of, what materials need to be transported across the cell membrane, and the types of • Review engineering design process	Teacher: • Facilitate review Students: • Participate in review
Body (15 minutes)		• Students will be given time to work on their cell membrane and transport analysis and engineering design worksheet	Teacher: • Pass out analysis worksheet if students haven't already gotten them • Circulate as students fill out their analysis worksheets, they may work with their group members • Answer any questions students may have. Students: • Fill out analysis worksheet to be turned in as part of their grade
Closure (10 minutes)		• Students will be given their post assessment, which corresponds with their pre-assessment on cell membrane, engineering design and their perceptions of engineering design	Teacher: • Pass out post assessment • Collect completed post assessments

			Students: • Complete Post-assessment

PART V: Student Handouts/Worksheets/Resources

See Appendix A-E
PART VI: Assessments.
Each group will be evaluated on their model and its structural accuracy, ability of their membrane to pass materials,
Each individual student will be assessed on their analysis questions and explanation of their designs.

Assessment Rubric for Cell Membrane Engineering Design				
Group Work - out of 15 possible points (Teacher will take into consideration any student absences or any other issues that arise and are brought to my attention during the project when assigning grades)				
	Very Proficient (3)	Proficient (2)	Unsatisfactory (0-1)	Points
Structural Accuracy	The model successfully demonstrates the structure of the phospholipid bilayer and transport proteins.	The membrane is a double layer and phospholipids are relatively similar to their actual structure. Transport proteins are not embedded in the membrane and/or carrier proteins cannot repeatedly modify their form to attach with their associated substrate, pass it through the	The membrane is a double layer, however, the model does not demonstrate the structure of the phospholipids (phosphate heads and fatty acid tails). Transport proteins are not embedded in the membrane.	/6

		membrane, and release it.		
Ability of membrane to pass materials • Sand (O_2/CO_2) • Water (Water & Ions) • pom-poms (glucose) • marbles (mineral ions)	Membrane was able to pass the majority (over 50%) of the materials through. The active transport pumps/carrier proteins were able to be reused	Less than half of the materials were able to pass through the membrane and the active transport pumps/carrier protein channels were only somewhat reusable	Little to no materials could pass through the membrane and the active transport pumps/carrier protein channels were non-functioning.	/3
Group Explanation of Model	The group gave an in depth explanation of every part of their cell membrane model	The groups explanation was somewhat thorough, but they missed one to two	The groups explanation was not adequate and they missed the explanation of three or more of the	/3
Participation in Team Presentations	All team members participate for about the same amount of time or at least all contribute heavily to the presentation	All team members participate, but not equally.	Not all team members participate; only one or two speak/participate	/3
BONUS POINTS* The team who is able to build a functional and accurate model at the lowest cost receives 2 extra points towards their group's grade.				
Individual Assessment out of 30 possible points				

Engineering design packet and analysis questions must be completed accurately and turned in.	/30
Total Score	/45

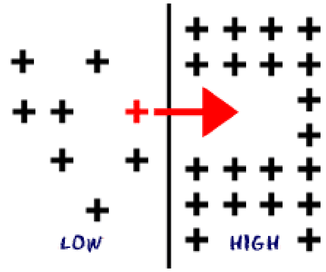
PART VII: References

https://www.uwstout.edu/slc/upload/transport_across_cell_membrane.pdf

Appendix A - Pre-Post Assessment

Section A

1. What is diffusion?
2. What type of molecule makes up most of the cell's plasma membrane?
3. What type of transport does this image represent?



4. What type of cellular transport requires energy?
5. The cell membrane contains channels and pumps that help to move certain materials from one side to the other. What are these channels and pumps made of?
6. Section B
7. What is engineering?
8. Describe the engineering design process. Use a diagram to illustrate your answer.
9. Is the engineering design process linear or cyclical? Explain your answer.
10. What is the difference between the scientific method and the engineering design process?
11. What is a design challenge in engineering?
12. What is a design solution in engineering?

Appendix B – Engineering Design Packet – 8 pages (For Students)

Name: ____ Period: ________ Date: ____________

Engineering Design Worksheet: Cell Membrane Model

Group Members: ____

Scenario:

German physiologist Rudolph Virchow first theorized cellular pathology--disease at the cellular level--in the 1850s. Today, new treatments for many disorders are a direct result of understanding a disease process at the cellular level. Abnormalities in organelles such as the cell membrane, can cause whole-body symptoms.

Cystic fibrosis was first described in medical journals in the late 1930's as a defect in the pathways leading from certain glands. This caused an array of problems including thick mucus in the lungs and frequent infection; a clogged pancreas, preventing digestive juices from reaching the intestines; and salty sweat. Cystic fibrosis is just one example of how genetic abnormality causes symptoms felt at a whole-body level.

The plasma membrane plays an integral role in maintaining homeostasis by controlling what comes into and out of the cell. We have discussed how small defects that result in some loss of function of the plasma membrane can result in major disorders, such as Duchenne Muscular Dystrophy and Cystic Fibrosis.

Some small, non-polar molecules are able to cross the plasma membrane along the concentration gradient directly through the phospholipid bilayer. Other smaller charged molecules, like water and charged ions, are able to cross the membrane via channel proteins through the process of facilitated diffusion. Some substrates need to be pumped across the membrane against the concentration gradient (or may be too large to cross the membrane) and require an energy input and/or the help of carrier proteins to cross the membrane via active transport.

In this design challenge, you will be acting as biomedical engineers who are responsible for designing a cell membrane that allows different substrates to cross it via a variety of "transport and channel proteins" to replace the faulty membranes in cystic fibrosis patients.

Your model should demonstrate the phospholipid bilayer and include representations of: Hydrophobic tails, Hydrophilic heads, Transport proteins, Channel proteins and Cholesterol that will be able to transmit four materials that represent different types of substrates that would need to enter/exit a cell. These substances may enter via simple diffusion, facilitated diffusion or active transport. Your prototype must represent each of these processes in the sense of whether or not extra energy (ATP) is needed. You will also have a budget of $25 to spend that you MAY NOT EXCEED. You will fill out a materials and cost slip to be given to the "materials supplier."

Here are the materials that will need to cross your model membrane, the type of cell transport they would require, and what will be representing each:

Substance:	Type of Cell Transport:	Represented by:
O_2/CO_2	Simple Diffusion	Sand
Water & Ions	Facilitated Diffusion via channel proteins	Water
Glucose (Moving against the gradient: ex. intestine)	Active Transport via specialized transmembrane proteins	Pom-Poms
Mineral ions (moving against the gradient: ex. in plant roots)	Active transport via specialized transmembrane proteins	Marbles

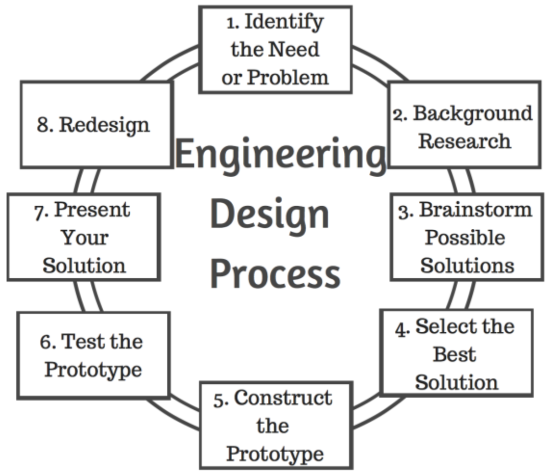
Materials Available:

- Styrofoam ball - $5.00
- Tape (6”) - $ 3.00
- Cotton balls (x5) -$3.00
- Toothpicks (x10) - $ 2.00
- Drinking Straw - $1.00
- Coffee Stirrers (x5) – $2.00
- Rubber Band – $3.00
- Paper Clips (x 5) - $1.00
- Craft Foam (2”x4”) - $2.00
- String (6”) - $2.00
- Cheese cloth (2”x2”) - $1.00
- Pipe cleaner – $1.00
- Aluminum Foil (2”x2”) - $1.00
- Play-doh (1” ball) – $3.00
- Q-tips (x20)-$3.0**0**

Appendix B: Design portfolio

Name____Period________Date___________

Cell Membrane Model Design Process Worksheet



Part I

Directions: Use this worksheet to ensure you complete every step in the Design Process. Use the spaces provided to show your work. If you need more room, you may attach additional pieces of paper. You must have the teacher check and sign each completed step before you begin the next one.

Step	Write your responses in these blocks.
1. Identify Problem or Challenge (everyone must answer)	Design a 3-D model of a plasma membrane that must allow different substrates to cross it via a variety of "transport proteins."

1. Identify Problem or Challenge What are the requirements? (everyone must answer)	Create a Cell membrane prototype with the following parts: • Hydrophobic tails • Hydrophilic heads • Transport proteins • Channel proteins • Cholesterol Other requirements: - Make sure you can describe simple diffusion, facilitated diffusion and active transport; as well as point out which part of the membrane participates in each. - Know what materials will pass through the membrane via each type of transport

Step	
2. BACKGROUND RESEARCH Do this individually for 5-10 minutes (everyone must answer)	Sketch each type of transport mechanism that would be used in their cell transport model. You may use your notes, textbook, or the internet to help.

1. Identify Problem or Challenge What are the constraints? (everyone must answer)	Consider the challenges that would arise with transporting each type of substrate. Give a minimum of TWO constraints.

3. BRAINSTORM POSSIBLE SOLUTIONS Draw your design. Do this part individually. You will compare with your group during the next phase. (everyone must answer)	After looking at the materials being offered, draw your initial individual design idea here and list materials. (use the box on next page to draw your groups design)
4. SELECT THE BEST SOLUTION Only one group member needs to produce a collaborative design. Be sure to look over each of your group members individual designs first.	Draw your groups collaborative design here and list materials. Label at least one part that each member of your group has contributed to the design. Justify each piece of your design that you outlined in step 2.
4. SELECT THE BEST SOLUTION Gather necessary materials. (everyone must answer)	List the materials and supplies you will need for your design along with the pricing. I will give you your materials when you show me this step is completed. (Remember you can always change the initial list if you find you need to adjust your design)
Teacher Approval:	Once approved you may grab a materials cost slip, fill it out and hand it to the materials supplier.

5. CONSTRUCT THE PROTOTYPE Follow your plan and complete this part after you have built your prototype. (everyone must answer)	In this box, write any issues (if any) you had in building your prototype and any changes you may have made to original design blueprint.
Teacher Approval	
6. TEST THE PROTOTYPE (everyone must answer)	How did it work? Were your active transport/carrier proteins able to be reused? What percentage of sand could pass through? What percentage of water could pass through? What was the final total cost of your prototype?
7. PRESENT PROTOTYPE	Present your prototype to the class. • Be sure to explain all of the parts and processes of your membrane including: 1. *hydrophobic tails* 2. *hydrophilic heads* 3. *transport proteins* 4. *channel proteins* 5. *Cholesterol* 6. *simple diffusion* *7. facilitated diffusion* 8. *active transport.*
8. REDESIGN Does your cell membrane prototype meet requirements? (everyone must answer)	Compare your design to the requirements you listed in Step 1. Does it meet all of the requirements? If not, what didn't it meet and why not? Compare your design to the constraints you listed in Step 2. Does it meet all of the constraints? If not, what didn't it meet and why not?
8. REDESIGN (everyone must answer)	If you had to do it all over again, how would your planned design change? Why? (you should think about what you observed in other group's prototypes)

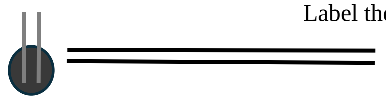
Appendix C – Analysis Packet

Name____ Period _______
Date______________

Cell Membrane and Transport Analysis

Define the following terms in your own words:

1. Cell membrane:
2. Phospholipid:

a.  Label the hydrophilic (head or tail) and the hydrophobic accordingly

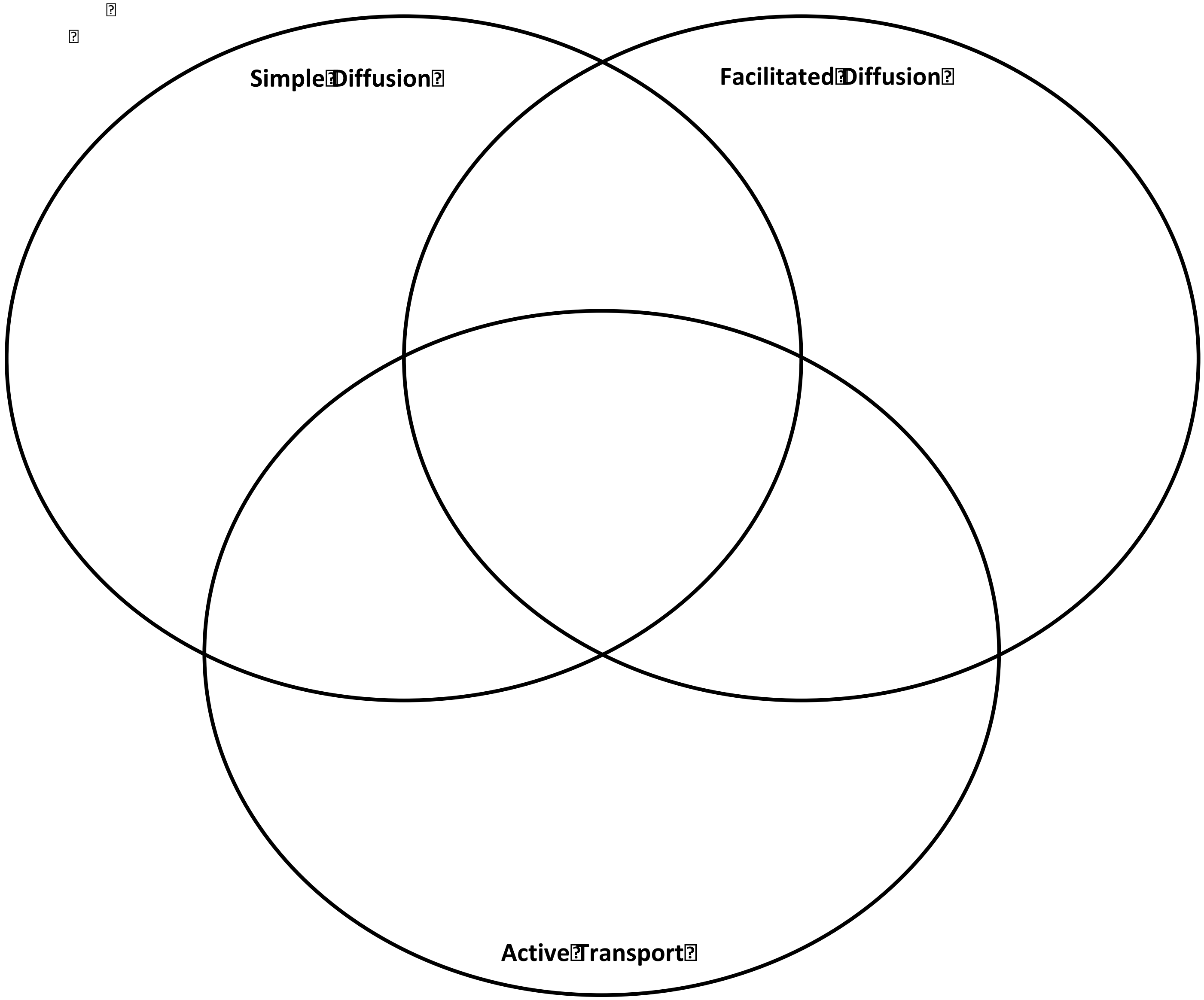
3. Receptor and signal molecules:
4. Selective permeability:
5. Transport protein channels:
6. Fluid mosaic model:
7. Diffusion:
a. Example of particles that diffuse through a cell
9. Active transport:
a. Examples of particles that use active transport through a cell

Answer the following questions referring to your prototype:

1. What part of your model represents the following:
a. Hydrophobic tails?
b. Hydrophilic heads?
c. Transport (carrier) proteins?
d. channel proteins?
e. Cholesterol?
2. How is diffusion different from facilitated diffusion?
a. Give an example of a molecule that does diffusion and one that does facilitated diffusion?
- Diffusion:
- Facilitated Diffusion:

3. Differentiate between active transport and diffusion.
6. How did completing this project help with your understanding of how a cell membrane works in a cell?
7. What do you think would happen if one of the components to the cell membrane- say the transport proteins- all were stuck open? Stuck shut? Be descriptive and scientific in your answer.
8. Do you think you would have been able to complete this project easier if you were working alone? Explain...

Appendix D – Venn Diagram



Appendix E: Group Materials and Cost outline

Group Members: ____

<u>Material</u> <u>Amount</u> <u>Cost</u>

Total Cost: __________

Group Materials and Cost outline

Group Members: ____

<u>Material</u> <u>Amount</u> <u>Cost</u>

Total Cost: ____________

Group Materials and Cost outline

Group Members: ____

<u>Material</u> <u>Amount</u> <u>Cost</u>

Total Cost: ___________

Group Materials and Cost outline

Group Members: ____

<u>Material</u> <u>Amount</u> <u>Cost</u>

Total Cost: ____________

Appendix 2- Teaching Engineering Self-efficacy Survey

Below are the items of the TESS instrument used for this study. The responses for this instrument are 6-point Likert scale ranging from 1 for Strongly Disagree to 6 for Strongly Agree.

Engineering pedagogical content knowledge self-efficacy (KS)

1. I can discuss how engineering is connected to my daily life.
2. I can recognize and appreciate the engineering concepts in all subject areas.
3. I can spend the time necessary to plan engineering lessons for my class.
4. I can employ engineering activities in my classroom effectively.
5. I can craft good questions about engineering for my students.
6. I can discuss how given criteria affect the outcome of an engineering project.
7. I can guide my students' solution development with the engineering design process.
8. I can gauge student comprehension of the engineering materials that I have taught.
9. I can assess my students' engineering products.

Engineering engagement self-efficacy (ES)

10. I can promote a positive attitude toward engineering learning in my students.
11. I can encourage my students to think critically when practicing engineering.
12. I can encourage my students to interact with each other when participating in engineering activities.
13. I can encourage my students to think creativity during engineering activities and lessons.

Engineering disciplinary self-efficacy (DS)

14. I can calm a student who is disruptive or noisy during engineering activities.
15. I can get through to students with behavior problems while teaching engineering.
16. I can keep a few problem students from ruining an entire engineering lesson.
17. I can control disruptive behavior in my classroom during engineering activities.
18. I can establish a classroom management system for engineering activities.

Outcome expectancy (OE)

19. When a student gets a better grade in engineering than he/she usually gets, it is often because I found better ways of teaching that student.
20. When my students do better than usual in engineering, it is often because I exerted a little extra effort.
21. If I increase my effort in engineering teaching, I see significant change in students' engineering achievement.
22. I am generally responsible for my students' achievements in engineering.
23. My effectiveness in engineering teaching can influence the achievement of students with low motivation.

Manuscript 3

Pre-Service Teachers' Implementation of Engineering Design Integrated Science Instruction

Abstract

The study explores secondary science preservice teachers' (PSTs) implementation of engineering design integrated science instruction (EDIS) during student teaching, utilizing a situated learning theory. It assesses how PSTs planned and implemented EDIS lessons, emphasizing their innovation in integrating engineering design with science teaching. Data from EDIS units, classroom observations, and interviews indicate a significant representation of innovation and adaptation in the PSTs' teaching methods, with most PSTs successfully embedding engineering design principles in their lessons. The findings show that PSTs not only grasped engineering concepts but were also able to creatively apply and adapt these in educational settings, enhancing the learning experience. This suggests a positive impact of the intervention, highlighting the potential for such theories to improve science education. Through the integration of engineering design, it promotes a comprehensive understanding and practical application of STEM concepts among students.

The integration of engineering design into K-12 science classrooms has received much attention lately because the *Framework for K-12 Science Education* (National Research Council [NRC], 2012) and the Next Generation Science Standards (NGSS; NGSS Lead States, 2013) requires teachers to teach science using the engineering design process. The *Framework for K-12 Science Education* (NRC, 2012) suggests that "engagement in the practices of engineering design is as much a part of learning science as engagement in the practices of science" (p. 12) and that the integration of engineering design into science is critical for emphasizing "the importance of understanding the human-built world" and the value of Science, Technology, Engineering, and Mathematics (STEM) integrated learning and teaching (p. 2). These assertions are supported by research that suggests that integrating engineering design into science instruction can support science content learning among students (e.g., Levy, 2013). The implication of this shift to an emphasis on the integration of science and engineering design is that students are now expected to learn and apply engineering design practices in the context of science learning. As a result, engineering design has become one of the content areas that science teachers need to understand for them to teach science in a way that aligns with the NGSS (Bybee, 2014).

Although the NGSS emphasizes the integration of engineering design in science teaching, few studies have looked at science pre-service teachers' (PSTs') planning for and implementation of engineering design integrated science (EDIS) lessons in schools (e.g., Capobianco & Rupp, 2014; Selcen Guzey et al., 2017). Furthermore, there is a lack of research on secondary science PSTs' planning and teaching engineering design integrated science (EDIS) lessons in schools. Much of this research focuses on teachers' perceived readiness and confidence in implementing engineering design and practices in the classroom (e.g., Haag & Megowan, 2015) or on teachers' understanding of and misconceptions about engineering and engineering design (e.g., Boesdorfer, 2017; Hynes, 2012; Yaşar et al., 2006). In general, research on teachers' perceived readiness and confidence in integrating engineering design and practice in their science classrooms suggests that, while most teachers agree that engineering integration should be included in K-12 science education, few are familiar with or confident about how to teach engineering in science classrooms (Yaşar et al., 2006). Similarly, in a national study of middle and high school teachers, participants rated training in engineering as the most needed type of professional development for improving their readiness to implement the NGSS (Haag & Megowan, 2015). This is not surprising, considering that only a few middle and high school science teachers have taken college courses in engineering (Banilower et al., 2018).

Teachers' lack of preparation in engineering is echoed in studies addressing teachers' understanding of engineering and engineering design. For example, Hynes, 2012 reported that middle school teachers showed inconsistent levels of understanding across the engineering design process (EDP) steps, with the strongest understanding of constructing prototypes and redesigning. Similarly, Boesdorfer (2017) said high school chemistry teachers held naive views of engineering, including that engineers fix things and that engineering and science are more closely related than they are. These views persisted even following an engineering training intervention. In contrast, Cunningham et al. (2007) indicated that, following the intervention, teachers showed significant increases in their comfort with and knowledge about engineering design, and nearly all participants who were teaching the following year implemented an engineering design project in their classrooms. Although there have been studies that looked into PSTs' implementation of engineering design (e.g., Maiorca & Mohr-Schroeder, 2020; Pleasants et al., 2020; Tank et al., 2020), little is understood about how secondary science PSTs' plan implement, possibly innovate on what they were taught during teacher preparation. Therefore, there is a need for more research on PSTs' planning and implementation of EDIS lessons after an EDIS intervention. This requires a theoretical framework through which the planning and implementation of EDIS lessons will be analyzed and discussed. Next, we address the purpose of this study and the research questions.

Purpose of the Study

This study will report on how secondary science PSTs participating in an intervention driven by the situated learning theoretical framework (McLellan, 1996) learned and used EDIS instruction in schools during their student teaching experiences.

Research Questions

1. After completing an EDIS intervention, how did PSTs plan and implement EDIS lessons in schools during student teaching?
2. To what extent did preservice science teachers innovate upon what they learned in the science methods course about engineering design to support their EDIS instruction during student teaching experiences?

Literature Review

While some studies have addressed teachers' understanding of and perceptions of preparedness for engineering and EDIS instruction, few studies have looked specifically at how secondary science teacher training affects in-service teachers' planning and implementation of engineering design in science instruction in schools. Studies that do exist suggest mixed results. For example, Capobianco and Rupp (2014) found that teachers could demonstrate strong planning skills for engineering design-based instruction, including incorporating engineering practices and alignment with content and design standards. However, classroom observations indicated that classroom instruction did not fully align with teachers' well-conceptualized plans. Researchers found that, in practice, teachers tended to spend most of their instructional time on the initial stages of the design process, including problem identification and planning, leaving little time for testing, redesigning, and communicating results. Capobianco and Rupp pointed to other literature that suggests that translating planning into action can be challenging for teachers and suggested that a greater conceptual understanding of both science and engineering is needed for successful enactment.

Unlike the participants in Capobianco and Rupp's (2014) study, Boesdorfer's (2017) study found that teachers understood and thoroughly incorporated developing solutions from scientific knowledge and experimentation and that teachers understood the necessity of a real-world problem for the enactment of engineering design. However, they struggled to incorporate student-centered problem definition, and most failed to incorporate the iterative nature of engineering design in their lessons. Boesdorfer suggested that more sustained professional development is necessary to ensure the full enactment of engineering design in science classrooms. Boesdorfer's suggestion for sustained professional development was evident in (Guzey et al., 2019a). Guzey et al.'s case study of one middle school life science teacher indicated that as the years passed, the teacher's instruction moved from a superficial integration of engineering into science in the first year, in which engineering was an add-on activity that did not facilitate science learning, to an explicit integration of engineering and science in the third year, in which students learned science *through* engineering.

Shifting from in-service teachers to PSTs, the study by Mumba et al. (2023) focused on the impact of an intervention on PSTs' integration of engineering design in a science methods course for secondary science PSTs. The findings revealed that PSTs successfully developed instructional materials that integrated science and engineering in line with NGSS guidelines. This approach empowered them to treat engineering as a core component rather than an add-on in lesson plans. The exposure boosted the PSTs' enthusiasm for including EDIS teaching in compliance with educational reforms. Although the study had a limited sample size, the results indicate that this method can improve PSTs' planning skills for such integrated lessons and positively influence both instructional practices and student learning, laying the groundwork for future research. In a related study, Ryu et al.'s (2019) study found that practicum experiences significantly shaped how secondary PSTs approached integrated engineering design in science teaching. Influenced by their backgrounds and interests, PSTs employed varied strategies for lesson planning. The practicum highlighted challenges like school culture, limited engineering knowledge, and a lack of role models, which could impede innovative teaching methods. Despite these hurdles, the experiences also enabled PSTs to understand the importance of engineering integration, factoring in student interests, curricular standards, and local context.

The aim of Maiorca and Mohr-Schroeder's (2020) study was to investigate the manner in which elementary PSTs created integrated STEM lesson plans by employing the EDP. These integrated STEM lesson plans were characterized as having open-ended tasks that utilized the engineering design process to instruct in math, science, and/or technology while adhering to the Framework for Quality K-12 Engineering Education (FQEE; Moore et al., 2014). The research discovered that while merging science, math, and engineering presented challenges, the majority of PSTs effectively combined engineering and math but had difficulty incorporating science. Utilizing engineering design as a framework for integration enabled PSTs to find linkages between content domains, and collaborative work was uniformly integrated into the lesson plans.

Nevertheless, the PSTs were inexperienced in comprehensive STEM tasks, which created obstacles in outlining how pupils would articulate their models. The study advised offering additional assistance and directions to PSTs in STEM teaching and emphasized the critical role of engineering in amalgamating science, technology, and math in educational settings.

In a similar study, Tank et al. (2020) aimed to investigate the manner in which elementary PSTs implemented instruction based on engineering design after undergoing engineering-focused professional development. The focus was specifically on the inclusion of engineering and its design elements. The study employed multiple frameworks for analysis, including the K-12 Framework for Science Education (NRC, 2012), the Next Generation Science Standards (NGSS Lead States, 2013), and the FQEE (Moore et al., 2014). The investigation featured 20 groups of elementary school teachers organized in triads, and data from these groups were scrutinized through the lens of the FQEE. The results identified four primary methods by which these teacher triads executed engineering design-centric instruction and pinpointed six crucial attributes for effective implementation. The research recommends that subsequent professional development should explicitly highlight and scaffold these essential attributes to enhance high-caliber instruction in elementary settings, in line with national educational reforms and scholarly guidelines on STEM integration.

Rationale for the Study

As evidenced in the review above, research is beginning to emerge addressing teachers' ability to plan for and implement engineering design in science classrooms. Of note, however, is that most of the studies reviewed above were on in-service science teachers and elementary PSTs. There is little research that reports on secondary PSTs planning for and implementing engineering design in science classrooms. Yet, the successful implementation of engineering design in secondary schools will also rely on PSTs' ability to plan and teach EDIS lessons in science classrooms. Therefore, this study reports on the efficacy of a science methods course aligned with situated learning theory (McLellan, 1996) on secondary science PSTs' planning and teaching EDIS units in schools during their student teaching. This study not only provides an explicit intervention model designed to teach science PSTs about engineering design and how to develop and implement EDIS instructional units, but it also grounds the intervention and preparation within the context of a theoretical learning framework – situated learning theory.

Significance of the Study

Literature shows that many studies on science teacher preparation in engineering design are generally not explicitly grounded in theoretical frameworks of learning (e.g., Conley et al., 2000). As a result, the science education community does not have an accurate understanding of how science PSTs learn how to plan and teach EDIS lessons in schools. Furthermore, this study contributes to the existing literature on engineering design in science teacher education by examining secondary science PSTs as they learn about engineering design in their science methods course and as they implement and reflect upon the realities of implementing an EDIS unit in schools. As such, this study broadens our understanding of how secondary science PSTs plan, teach, and reflect on their EDIS instructional practices in schools.

Theoretical Framework

This study will be informed by the situated learning theoretical framework, which suggests that "knowledge is situated, being in part a product of the activity, context, and culture in which it is developed and used" (Brown et al., 1989, p. 32). That is, conceptual and practical knowledge are inseparably woven within the context in which they are learned. This knowledge is dynamic, changing as additional experiences lead to refined understanding (Brown et al., 1989). Central to situated learning theory is the idea that knowledge construction is contextual and collaborative and that effective learning allows for a cognitive apprenticeship in which learners learn concepts in authentic contexts through collaborative engagement with others (McClellan, 1996).

These characteristics of situated learning theory mirror the elements of our science methods course in which the EDIS intervention was done. For example, the community of practice includes both science PSTs (novices) and engineering design instructors (experts) in our intervention. Science PSTs experienced authentic learning by engaging in *informed EDIS* instruction through activities. Collaboration between science PSTs and the experts in the implementation of EDIS units and opportunities for PSTs to reflect on their EDIS instruction in schools align with the cognitive apprenticeship.

McClellan (1996) suggests a model of instruction based on situated learning theory that includes four main components: Cognitive apprenticeship and coaching, multiple opportunities for practice, collaboration, and reflection. *Cognitive apprenticeship* allows learners to learn and apply new skills in authentic contexts. For example, in this study, PSTs learned a new method of science instruction by observing the expert (in this case, the science methods course instructors) model the EDIS teaching and its related instructional behavior and language. Then, PSTs applied the method through EDIS unit development and teaching in the contexts for which the methods were designed (e.g., the science classroom). Throughout the cognitive apprenticeship, instructors act as *coaches* by using scaffolding to support and guide learners as they construct and apply their knowledge. In this study, science PSTs learned new skills and were provided *multiple opportunities* to practice the new skill (in this case, the EDIS teaching method) to further refine and generalize their skills to new contexts. This refinement can occur through *collaboration*, as science PSTs engage in conversation with their community of practice, including both course instructors and other PSTs, to synthesize their experiences and refine their understandings. Through this discursive and collaborative engagement, PSTs were able to *reflect* on their learning and application experiences by observing, predicting, inferencing, and theory-building.

We believe this study extends previous studies on teacher training in situated learning on how to teach science (e.g., Bell et al., 2013). However, to our knowledge, this is the first study to examine the efficacy of a science methods course aligned with the situated learning theoretical framework on science PSTs' planning and implementing EDIS units in schools during their student teaching. The main goal of our instruction in science methods course is for science PSTs to transfer what they learn about engineering design and EDIS teaching to science classrooms in schools.

Science Methods Course Alignment with Situated Learning Theory

As mentioned above, the theory of situated learning (McLellan, 1996) guided the instruction of the science PSTs both during their methods course and during their student teaching placements. Next, we discuss how the components of situated learning theory - *cognitive apprenticeship and coaching, opportunities for multiple practice, collaboration, and reflection* – map onto the science PSTs' learning of the EDP and how to integrate it into science teaching.

Cognitive Apprenticeship and Coaching.

In cognitive apprenticeship, novices first observe the expert modeling appropriate behavior and language. This allows novices to absorb the "culture of practice" or see what they need to do in order to become masters (Lave & Wenger, 1991, p. 95). Similarly, PSTs engaged in a cognitive apprenticeship throughout the science methods course and student teaching placements. Instructors not only explained how to plan for and implement EDIS units within science classrooms but also provided justifications for certain instructional choices. PSTs were aware of the rationale and thought process behind specific steps of the EDP. For example, instructors provided the participants with several explanations for how and why brainstorming should often occur within the context of a group. At the heart of situated learning and cognitive apprenticeship lies the belief that knowledge is to some extent shaped by the activities, contexts, and cultural settings where it emerges and is applied (Brown et al., 1989). Thus, PSTs continued to learn about how to integrate engineering design into science teaching while they were in their student teaching placements with the support of course instructors.

Coaching within the situated learning theory can be described as "observing students while they carry out a task, providing a "guide on the side" who intervenes and provides scaffolding for learning to progress, when necessary, but otherwise fades into the background, providing learning with opportunities for initiative and self-direct problem-solving: constructive learning" (McLellan, 1996, p.11). In this sense, PSTs were exposed to multiple instances of coaching. For example, PSTs were also given a chance to practice instructional strategies during a scenario activity in which several PSTs acted as high school students learning engineering design. The remainder of the PSTs then talked through potential solutions and teaching strategies that could be used to enhance student learning in those instances.

Opportunities for Multiple Practice.

Opportunities for multiple practice is an essential component of situated learning theory. Through repetitive practice, "skills are honed through practice, where the student moves toward flying solo, without the support of a teacher and coach" (McLellan, 1996, p.12). PSTs had opportunities throughout the methods course as well as during their student teaching to practice planning for and implementing an EDIS unit. For example, during both their science methods course and student teaching, PSTs were tasked with developing an EDIS unit and activities. During the methods course, PSTs developed these lessons under the guidance of the course instructors and received multiple rounds of feedback. They were also engaged in teacher guide manuals in which they explained the rationale for integrating engineering in science teaching and detailed procedures for developing EDIS units and activities. The detailed procedures were illustrated in their EDIS units.

Collaboration and Reflection.

PSTs are engaged in collaboration while learning about how to teach engineering design in science classrooms and while actually implementing their lessons. In their methods courses, PSTs worked with their instructors, mentor teachers, and peers to complete engineering design tasks, review previously developed EDIS unit plans, and discuss specific teaching strategies.

Intervention in Science Methods Course

The secondary science teacher education program, in which participant PSTs were enrolled, required them to complete two science methods courses, one in the fall and another one in the spring semester. In the fall semester, prior to the study, PSTs were enrolled in the first science methods course that addressed the following topics: the rationale for science teaching in schools, the nature of science, lab safety, science process skills, conceptual change, misconceptions in science, constructivism theory, features of inquiry instruction, technology integration in science teaching, and how to assess student learning. PSTs also learned how to teach science through the following instructional models: guided instructional practice, inquiry, predict-observe-explain (POE), 5E learning cycle, stations, demonstrations, discrepant events, target inquiry labs, argumentation, and case-based learning.

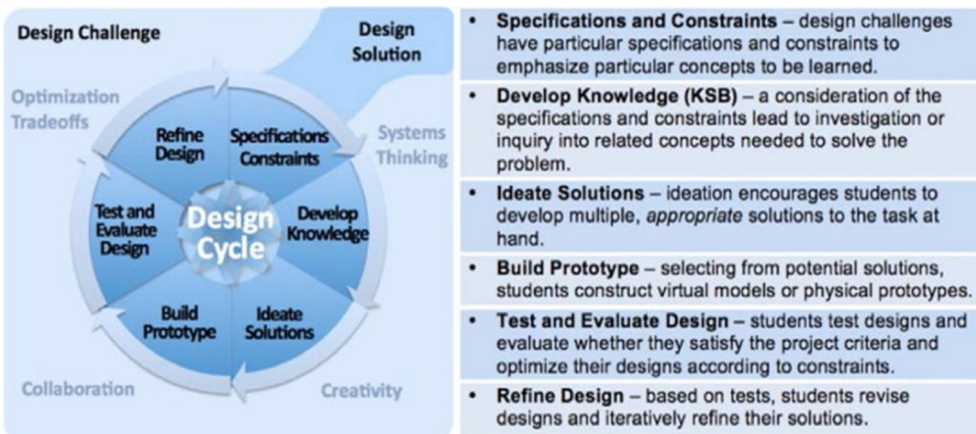
In the spring semester, PSTs were enrolled in the second science methods course, where they learned about project-based and problem-based teaching strategies, the NGSS, the EDP, how to develop EDIS unit plans, and best practices for teaching and assessing student learning in EDIS lessons. The intervention on the NGSS practices, engineering design, scientific method, and how to integrate engineering design into science teaching was done over six weeks. The intervention was done by four instructors: Two engineering professors, one engineering education professor, and one science education professor. The learning objectives for EDIS intervention were for PSTs to become familiar with the *New Framework for K-12 Science Education* (NRC, 2012) and the NGSS (NGSS Lead States, 2013), learn how to read the NGSS, describe the three dimensions of the NGSS, understand, and apply disciplinary core ideas, cross-cutting concepts, and science and engineering practices, understand and apply EDP; engage in EDIS activities develop understanding of similarities and differences between engineering design and scientific method; develop teacher guide manuals for how to develop EDIS lessons and activities; develop and teach EDIS units and activities, create a collection of EDIS teaching and learning resources, and demonstrate how to assess student learning in EDIS teaching.

Instructional Model

We used the informed engineering design model (See Figure 1) (Chiu et al., 2013) to teach engineering design in our intervention (See Figure 1). The informed design model has the following design elements: identifying the design challenge, identifying specifications /constraints, developing knowledge, ideating solutions, building prototypes, testing and evaluating designs, and refining designs. The informed engineering design framework is designed to help make engineering design processes explicit for teachers or students. The informed engineering design framework guides learners in developing engineering design skills and science concepts through inquiry.

Figure 4

Engineering Design Instructional Model (Chiu et al., 2013)



During the intervention, the informed engineering design instructional model was embedded in the WISEngineering online learning platform to help teacher candidates understand engineering principles and design processes. WISEngineering platform extends Web-based Inquiry Science Environment (WISE) (Slotta & Linn, 2009) by leveraging the support for scientific inquiry to support engineering design. For example, instead of scaffolding PSTs' inquiry questions, the prompts in WISEngineering supported PSTs to define the problems by identifying specifications and constraints. Features such as the Design Wall enabled PSTs to critique and build upon others' solutions by posting designs and commenting. The design journal kept track of everything the PSTs generated within WISEngineering, including drawings, answers to embedded assessments, posted designs, and critiques of others' work. Within the Design Journal, PSTs selected and annotated specific artifacts to include in their Design Portfolio, which they shared with instructors or their peers. Both the Design Journal and

Portfolio facilitated authentic engineering practices as well as reflection. Additionally, WISEngineering leverages the core functionality of the WISE system, including assessment, instructor monitoring, and researcher tools. Using WISEngineering, PSTs monitored their progress, received real-time feedback on their work, and customized the projects for their own contexts and communities. Embedded assessment technologies enabled instructors and researchers to capture PST thinking during the projects.

Intervention Activities

The intervention objectives were achieved through lessons and activities and the development of EDIS instructional materials. First, PSTs learned about the principles of engineering, the role of engineering in society, and prominent engineers in the US. After a formal introduction to engineering and engineering design, PSTs were engaged in hands-on engineering design activities and critically evaluated them from both the student's and teacher's perspectives. PSTs were introduced to Engineering Teaching Kits (ETKs) (Richards et al., 2007). ETKs were designed for use in middle school and high school science classrooms with the purpose of teaching engineering and science principles and practices to students through real-world design challenges. For example, one of the activities challenges students to use their knowledge of physics, energy, force, and friction to design a solar-powered car that can pull a load (Schnittka & Richards, 2016). After engaging with the ETKs, PSTs discussed the successes and challenges of the activities from both student and teacher perspectives.

Second, PSTs participated in an activity where they were challenged to build a solar-powered car using the materials that were provided (Schnittka & Richards, 2016). In this activity, PSTs learned about solar energy, the EDP, and NGSS practices by responding to the design challenge. PSTs defined the challenge, developed knowledge, redefined the problem, ideated solutions, built prototypes, tested and evaluated the prototypes, and revised their prototypes. PSTs then presented their cars, the design process, energy transformation processes, and their reflections on the design process to the class.

Second, PSTs learned about the similarities and differences between the scientific method and the EDP through activities that illustrated both processes. Specific examples were provided during the discussion. For example, during the solar-powered car activity, PSTs were asked to identify the NGSS practices that applied to the EDP and the scientific method, and both. PSTs learned how the EDP is similar to, but different from, the scientific method, as this is an area that is essential for teachers to understand for effective integration of engineering design and science in science classrooms. Similarities between the two processes emphasized during the intervention include the cyclical (iterative) nature, the identification of a problem or question, the need for background research, the need to make observations, the need to conduct a test, data collection, and the need to communicate findings. When highlighting the differences between the two processes, central to the conversation was the fundamentally different purpose of each process: Engineering design is used to create solutions for real-world problems, and the scientific method is used to discover information about the natural world.

Third, PSTs were engaged in a resource collection assignment that was designed for PSTs to create a collection of digital and non-digital engineering design resources they would use to teach EDIS in middle or high school science classrooms. Specifically, each PST was required to identify ten engineering design resources, and each resource should address one or more science concepts. For each resource, PSTs were asked to provide the following information title, science concepts/topics the engineering design resource would address, a brief description of how the resource would be used to teach science concepts and engineering design in science classrooms, science and engineering practices, disciplinary core ideas, and crosscutting concepts the resource is addressing, and modification(s) they would make for the engineering design resource to effectively address the identified science concepts. PSTs were also asked to acknowledge the sources of the engineering design they had provided in the assignment, and where possible, they were asked to provide screenshots of the websites where they got the engineering design resource.

Fourth, PSTs were involved in analyzing commercially prepared EDIS activities for representation of the EDP and science and engineering practices prescribed in the NGSS. The goal of this activity was for PSTs to learn how to identify science and engineering practices in activities prepared by others before they started developing their own activities. PSTs were engaged in characterizing EDIS activities from online sources [TeachEngineering-https://www.teachengineering.org/; tryengineering (tryengineering.com); and engineering is elementary (eie.com]) for the nature of integration using a continuum model which identifies activities into five categories: *Independent engineering design, Engineering focused, Balanced engineering design and science, Science focused and Independent Science* (Mumba et al., 2017). The goal of this activity was for PSTs to gain the skill for determining the nature and extent to which engineering design and science are integrated into commercially prepared activities.

Fifth, PSTs adopted the teacher role as they learned about the EDP, teaching strategies, and methods of assessing student learning in EDIS classrooms. Then, PSTs developed their own EDIS units in order for them to demonstrate their instructional planning skills. PSTs gathered resources, created teacher guide manuals, and developed EDIS units to be used in their student teaching classrooms in the fall 2017 semester. Sixth, the PSTs were engaged in developing a teacher-created teacher guide manual for how to create EDIS units. The EDIS teacher guide manuals were accompanied by illustrative EDIS units. The creation of these artifacts demonstrated their knowledge of the EDP and skills for developing EDIS curriculum materials. Throughout the intervention, PSTs frequently presented their work and discussed their EDIS units with peers and instructors to receive feedback, thus reinforcing the iterative design process and the collaboration and reflection elements of the situated learning theoretical framework.

Student Teaching

In fall 2017, fall 2018, and spring 2019, cohorts of participant PSTs were student teaching in schools under mentor teachers. Instructional coaches also supervised our PSTs during student teaching. Participants taught in the following content areas: Biology or Life Science, Earth Science, Chemistry, and Physics. During student teaching, PSTs were required to teach several lessons for teacher education requirements. However, each student teacher was required to teach six lessons, which were observed by the university supervisors, provided feedback, and assigned a score. All PSTs were assessed for instructional planning and actual teaching. As part of the Noyce scholarship requirement, all PSTs were asked to implement EDIS lessons or units during student teaching. To ensure PSTs were able to implement EDIS lessons, the Noyce project provided money for instructional materials. Participants were not evaluated on whether they incorporated engineering design in their science instruction, nor were mentor teachers selected to promote the use of EDIS lessons. However, mentor teachers allowed our PSTs to teach EDIS lessons. Some mentor teachers allowed PSTs to modify their inquiry labs into EDIS labs. EDIS instruction was new to most mentor teachers.

Student Teaching Seminar

A 3-credit hour seminar course was offered concurrently with student teaching experience. The purpose of this seminar course was to reinforce what was learned in the science methods courses within the context of the participants' student teaching experiences. PSTs received more instruction on engineering design and how to integrate engineering design in science classrooms. A significant amount of time was devoted to helping PSTs learn how to develop more EDIS activities. Another major component of this course was devoted to teacher induction, mentoring, and the teacher hiring process. School leaders from local school districts served as guest instructors on these topics. We also devoted time to preparing for the state science teachers' conference, which was held at the end of the semester.

PSTs worked in small groups to prepare an hour-long interactive presentation on engineering design, Problem-based learning, and inquiry instruction. PSTs also learned how to write grant proposals for funding, especially for engineering design integration in science classrooms. The design and implementation of the seminar course reinforced what was taught in the science methods course and aligned with the situated learning model (McLellan, 1996). Instructors modeled specific examples of EDIS activities and provided support to PSTs during the planning and implementation of EDIS activities in schools. PSTs received feedback on their EDIS activities before and after implementing them in schools. One of the research assistants in the NSF project observed EDIS lessons in schools and provided feedback to PSTs on their instruction. PSTs were provided multiple opportunities to practice EDIS instruction through presentations of their EDIS units and activities to peers and instructors in science methods courses.

Before and during student teaching, PSTs were engaged in cognitive apprenticeship and collaboration by working closely with instructors who provided coaching, scaffolding, and detailed feedback in their EDIS instruction. Coaching was also a major component of the student teaching experience. One of the authors observed participants' classroom instruction and then provided constructive feedback and assistance in EDIS planning to participants. Collaboration was emphasized during the intervention in our methods course and during student teaching in schools. PSTs collaborated with each other through the sharing of instructional materials, resources, and feedback. Opportunities for discussion and reflection on their experiences with engineering design integration in science instruction were part of the seminar and science methods course. During the seminar class, students were given the opportunity to reflect on their implementation of EDIS and share with the class the successes and challenges they experienced in their classrooms. In summary, PSTs learned and transferred EDIS instruction with the situated learning model.

Methods

Participants

Participants were 45 secondary science PSTs who were enrolled in the secondary science teacher education program at a Mid-Atlantic research university. There were 38 female and seven male PSTs. Twenty-three (23) PSTs were in biology, 14 in chemistry, one in physics, 4 in environmental science, and 3 in engineering. None of the PSTs had formal K-12 science teaching experience before participating in this study. Five PSTs had taken an engineering course in their undergraduate degree programs. Before they participated in this study, the PSTs had completed coursework in the following areas: adolescent learning and development, instruction and assessment, content area reading, exceptional learners, curriculum and management, technology, and science teaching methods.

Data sources

This study utilizes existing data that was collected in two NSF-funded research projects in 2016-2018. Participants' EDIS units, classroom observations, and interviews served as primary data sources. It is assumed these data sources will provide evidence of the degree to which participants transferred what they learned in the science methods course about engineering design integration in science instruction. It is further assumed these data sources will also provide evidence for the intervention's impact on PSTs' ability to integrate engineering design into science instruction. The following elements were consistent across all PSTs' lesson plans: Virginia Standards of Learning (VA SOLs) and NGSS materials and resources needed for the lesson plan, an outline of the steps of the EDP and corresponding student and teacher tasks, and student assessments. After teaching their EDIS units, PSTs submitted all instructional materials, including student handouts and presentation slides, to researchers in the NSF-funded project.

EDIS Units

EDIS units created and taught in schools by PSTs were also collected. We also collected artifacts in the form of student work samples (e.g., design portfolios). Both EDIS units and artifacts served as valuable sources for establishing the quality and nature of engineering and science integration PSTs implemented in science classrooms during their student teaching.

Classroom Observations

Engineering design integrated science lessons were observed by a research assistant in the research project. While the EDIS units varied in length (90-540 minutes), all units spanned at least the entirety of one 90-minute class period. Some participants taught the same unit across different blocks of students. All the lessons were videotaped. The observations were conducted using the Engineering Designed Integrated Science Classroom Observation Protocol (EDIS-COP) (see Appendix A). The EDIS-COP observation protocol contained some items that were adapted from the Reformed Teaching Observation Protocol (RTOP) instrument (Sawada et al., 2002) and the mathematics integrated science classroom observation protocol (Judson, 2013). The protocol has 30 items designed to measure the following constructs: the purpose of integration, lesson design, and implementation. Within the constructs, there are six subscales: meaning and purpose, design and structure, lesson dynamics, EDP as a tool, procedural knowledge, and classroom culture.

Each item in the instrument was scored on a 0-4 scale, with zero indicating that the practice was not present and four indicating that the practice was very evident. The protocol has the contextual and background activities section where the observer gives a brief description of the lesson observed, the classroom setting in which the lesson took place (space, seating arrangements, etc.), and any relevant details about the students (number, gender, ethnicity) and teacher(s), that are important and useful in data interpretation. The observer was also encouraged to use diagrams if they seemed appropriate. The observer also took detailed field notes. Such field notes contained information that was not captured by the items in the observation protocol, such as conversations between the PST and the students.

Semi-Structured Interviews

After teaching their EDIS units, all PSTs formally reflected upon their practice through a semi-structured interview with one of the project researchers. The interviews lasted approximately 30 minutes and followed a semi-structured interview protocol (see Appendix B). All interviews were audio recorded and subsequently transcribed. In addition to asking the PSTs to explain various NGSS science and engineering practices, the PSTs were asked to reflect upon the development and implementation of their EDIS unit in schools. For example, the following interview questions focused on how well PSTs viewed their implementation: (a) To what extent did the lesson proceed as planned? (b) How well do you think engineering design was incorporated into the science content? (c) How (if at all) did you think engineering design helped the students learn better about the science content and engineering design in your specific unit? and (d) In your opinion, what component of the EDP did students struggle with the most? and (e) If you were to teach this unit again, what (if anything) would you do differently?

Data analysis

In the first phase of data analysis, the EDIS units were analyzed to assess how PSTs transferred their understanding of engineering design into science classrooms. The categorization procedure used by Bell et al. (2013) was adapted and modified for this analysis, involving three categories: Application, Adaptation, and Innovation. EDIS units, lessons, and activities developed and implemented by PSTs were categorized accordingly. The application category applied to EDIS units, lessons, or activities that have the same engineering design model and content with little or no modification from what was modeled/presented in the intervention in our science methods course. The adaptation category applied to EDIS units, lessons, or activities that have the same engineering design model participants experienced in our intervention, but the engineering design activities were adapted from other sources, not from our intervention. The innovation category applied to entirely new EDIS units, lessons, and activities PSTs created. This category will also include EDIS units that participants created by changing existing inquiry labs into EDIS lessons/units/activities. Percentages for each category were then computed out of the total units in the data set, serving as an indicator of the degree to which participants learned about engineering design and the extent to which they transferred it to science classrooms during their student teaching.

In the second phase of data analysis, units were analyzed for the quality of the EDIS units created and implemented by PSTs in schools using the curriculum evaluation tool created by Guzey et al. (2016) (See Appendix C). This evaluation rubric included nine specific ratings and one overall rating. We eliminated one specific rating – integration of math content – because math integration was not the focus of the EDIS units PSTs developed and implemented in schools. The remaining eight specific ratings were (1) A motivating and engaging context, (2) An engineering design challenge, (3) Integration of science content, (4) Instructional Strategies, (5) Teamwork, (6) Communication, (7) Performance and Formative Assessment, and (8) Organization. Each item in the rubric was evaluated on a 0-4 scale, with zero representing not present and four representing excellent. An overall rating was also determined for each PST.

In the third phase, lesson observations were analyzed. The protocol had 30 items designed to measure two main constructs: (a) purpose of integration and (b) lesson design and implementation. Within these constructs were six subscales: meaning and purpose, design and structure, lesson dynamics, EDP as a tool, procedural knowledge, and classroom culture. Each item in the instrument was scored on a 0-4 scale, with zero indicating that the practice was not present and four indicating that the practice was evident. The instrument summed up to a total of 120 points; however, a score over 60 indicated a reformed-based lesson. Descriptive statistics were then generated for total EDISCOP and the two constructs, as well as each of the six EDISCOP subscale scores associated with each of the PSTs.

The interviews were analyzed for evidence of intervention impact on PSTs and implementation of engineering design in science classrooms. Content analysis and constant comparative methods (Corbin & Strauss, 2008) were used. First, PSTs' responses were reviewed, identifying emerging themes across the three data sources. Then, the emerging themes were grouped into main themes. After the content analysis of the interviews, the three phases of the data analysis were combined for a final pattern analysis. This was done to obtain a holistic perspective of any apparent patterns in how the PSTs were designing and implementing their EDIS lessons as a group.

Positionality Statement

I am a male with a background in life sciences who grew up in the highly populated and homogenous city of Lagos, Nigeria. I began my tertiary education at the University of Lagos, earning a baccalaureate degree in Cell Biology and Genetics, then a Master of Science degree in Genetics. I then studied for a Master of Arts (MA) in Biotechnology at West Virginia State University before beginning my doctoral education here at the University of Virginia. I came in as an outsider to science education and EDIS instruction in school settings. While working as a graduate teaching assistant in a biology undergraduate program at West Virginia, I noticed some of the unique challenges that come with teaching science to educationally disadvantaged students. I observed that many students had a hard time relating to science, which caused a lack of interest in the subject. However, when the science they were taught in the classroom was relatable to their daily lives and culture, their interest increased. This sparked my interest in research in science instruction, leading me to a doctoral program studying how PSTs can enhance their science instruction through engineering.

It is important to recognize that besides being a researcher, I also co-taught similar science methods courses in subsequent years after data collection was done. While my teaching assistant role wasn't formally labeled as a data source, it afforded me the chance to observe and engage in dialogues with PSTs, enhancing my interpretation of their comprehension and application of engineering in their science instruction. Additionally, my position as a teaching assistant gave me authority when seeking student involvement, prompting us to establish safeguards to mitigate any sense of coercion stemming from my position of authority. For instance, as a component of this study, a neutral third party invited PSTs to partake in the research. This third party collected consent forms and withheld them from all involved researchers until the intervention was complete and grades were finalized. Therefore, I remained unaware of the participants until they concluded the program, and I no longer had power over them. Moreover, I did not grade any coursework in the science methods classes in which the data was collected. Through these precautions, it was our aim that the PSTs felt at ease participating, knowing that their participation would have no impact on their enrollment in the teacher preparation program or teacher certification process.

Results

This research aimed to explore the implementation of EDIS into science instruction by PSTs during their student teaching as part of a science teacher preparation program. This approach was anchored in the elements of situated learning theory. The study uncovered that the PSTs not only significantly embraced engineering design in their teaching practices but also aligned this integration with reform-based instructional strategies. Furthermore, the results highlight specific elements of the teacher preparation program that were instrumental in enabling this effective integration of engineering design into science lessons. A notable aspect of the teacher preparation program was its explicit objective to integrate engineering in the science methods course and to ensure PSTs integrated engineering design into their science teaching. Significantly, the successful implementation of this integration by the PSTs was not just a requirement but also a result of their pedagogical insights and a strong intrinsic motivation to enrich their science instruction through the integration of engineering design concepts.

Phase 1: EDIS Categorization

In the first phase of data analysis, the extent to which PSTs incorporated what they learned about engineering design into science classrooms was evaluated. The categorization of instructional materials revealed varying degrees of integration distributed among two of the three categories: Innovation and Adaptation. Out of the total units (45) analyzed, 26 (57.8%) were categorized under Innovation. This category represents the creation of entirely new units by the PSTs or the transformation of existing science inquiry labs into EDIS units. Adaptation, where the engineering design activities were sourced from other materials, not directly from the intervention, constituted 19 units (42.2%). Lastly, the Application category, which pertains to EDIS units that closely mirrored the engineering design model and content presented in the intervention with minimal modification, was not represented in the instructional materials analyzed. Table 1 below provides insight into the number of PSTs for the observed category-subject combinations.

Table 1: Distribution of EDIS Categories Across Subjects

Subject	EDIS Category	Number of PSTs
Biology	Adaptation	11
	Innovation	12
Chemistry	Adaptation	3
	Innovation	11
Environmental Science	Adaptation	1
	Innovation	3
Physics	Adaptation	4

The EDIS unit by Maxwell on osmosis is an example of an EDIS unit under the innovation category. Students were tasked with designing a liquid solution to prevent a potato from losing or gaining too much water, thus maintaining its mass, length, and turgidity. This activity required them to apply their knowledge of cell membranes and osmosis to create an isotonic solution. Through research, design, and testing of prototypes, students developed a deeper understanding of osmosis in a real-world context, enhancing their knowledge of biology and engineering design. In his interview, Maxwell answered the question about what integrating engineering design into science teaching means to him by describing the student-centeredness of EDIS teaching. He suggested that teachers should anticipate students' problems and plan their lessons accordingly.

> “Um, so I think it's- it's- it's a really good way of teaching science because it ... it's very student-centered… It's not really up to the teacher to figure out, Okay, this is how they're gonna do it. This is how they're gonna test it. Um, the teacher has to plan out, "Okay, what are their potential options?" And give them sort of a window of opportunity to test it- to do the engineering.”

On the other hand, Maxwell confirmed that the lesson had proceeded mostly as planned, but he had to make some adjustments along the way to ensure successful implementation. Also, when asked about his students’ performance, he noted that the primary struggle was with generating ideas.

> “I thought it proceeded pretty much exactly as I had planned. There were a few things where maybe I realized, "Okay, giving them a beaker would be easier so that they don't have to stick their hand in this test tube and get it all nasty.”

> “I think they struggled with coming up with ideas. Or coming up with ideas and selecting the best solution. Partially because, like I said, the way I structured it was they kind of only had

half of the information ... that they needed at first, and so I intentionally made it kind of challenging."

An example of an adapted EDIS unit was by Mara, which focused on creating biodomes to explore ecosystem interactions and energy dynamics (e.g., Beggs et al., 2006). Engineering design is integrated through tasks like brainstorming independent ecosystems, creating biodomes as self-sufficient systems, and understanding the engineering design process. Students developed prototypes, adapted designs based on new knowledge, and presented their work. While reflecting on her thinking behind adapting this EDIS unit for her science class, Mara shared her thought process in designing the biome bottle unit:

> "I thought the biome bottle would look more different when I originally thought of it. I thought maybe we could create like desert biomes, and like fresh water biomes, and like, tundra, and I realized that was very difficult to have this many students with that many different materials… And I mean, it was neat 'cause it was different, but I found it challenging to have more variation."

The results indicate an inclination towards innovation among PSTs. The Innovation category, representing the highest proportion of the units, underscores the PSTs' ability to create novel instructional materials, demonstrating a possible high level of understanding and application of engineering design principles. The Adaptation category, accounting for a third of the units, reflects the PSTs' skill in modifying existing resources to fit their instructional needs. Collectively, these findings suggest that the PSTs were not only able to understand and apply the principles of engineering design in their teaching but also displayed a range of competencies from application to innovative creation of EDIS instructional materials. With over 70% of the EDIS units analyzed falling under the innovation and adaptation categories, this analysis indicates that the PSTs gained significant expertise in engineering design integration from the science methods course.

Phase 2: Quality of EDIS Units

The second data analysis phase assessed the quality of the EDIS units created and implemented by the PSTs. Utilizing the curriculum evaluation tool by Guzey et al. (2016) (See Appendix C), the findings indicated varied levels of quality in the EDIS units implemented by PSTs. The units were assessed across eight specific ratings on a scale from 0 (not present) to 4 (excellent). Most of the ratings fell under either good (3) or excellent (4).

In the assessment of inter-rater reliability, the analysis focused on the consistency of ratings provided by the two independent raters. To quantify this reliability, Cohen's kappa coefficient was computed, a statistical measure that accounts for the possibility of agreement occurring by chance. After each rater independently evaluated the EDIS unit, Cohen's kappa was calculated to be 0.89. This value indicates substantial agreement between the raters, as per the guidelines suggested by Landis and Koch (1977). It is important to note that while a kappa value above 0.60 is generally considered indicative of significant agreement, our threshold for acceptable reliability was set at 0.70, considering the complexity of the data being analyzed. The high kappa value thus reassures the robustness of our coding process and the reliability of the subsequent analysis.

Table 2 below presents the rating distribution for the 45 EDIS units analyzed. The table indicates that most of the ratings fell under good or excellent, with consistent percentages over 70% when combined. The Teamwork subscale scored highest on the scale, with 18 EDIS units receiving a ‘good’ rating and 17 units achieving an ‘excellent’ rating. Similarly, the Instructional

Table 2: Rating Distribution for Quality of EDIS Units.

Subscales	Ratings				
	Not Present (0)	Weak (1)	Adequate (2)	Good (3)	Excellent (4)
A Motivating and Engaging Context	2.2% (1)	8.9% (4)	15.6% (7)	51.1% (23)	22.2% (10)
An Engineering Design Challenge	4.4% (2)	4.4% (2)	15.6% (7)	40% (18)	35.6% (16)
Integration of Science Content	2.2% (1)	4.4% (2)	20% (9)	48.9% (22)	24.4% (11)
Instructional Strategies	0	8.9% (4)	17.8% (8)	35.6% (16)	37.8% (17)
Teamwork	0	2.2% (1)	20% (9)	40% (18)	37.8% (17)
Communication	4.4% (2)	2.2% (1)	20% (9)	35.6% (16)	37.8% (17)
Performance and Formative Assessment	2.2% (1)	8.9% (4)	15.6% (7)	40% (18)	33.3% (15)
Organization	0	11.1% (5)	17.8% (8)	35.6% (16)	35.6% (16)
Overall	0	6.7% (3)	11.1% (5)	51.1% (23)	31.1% (14)

n = 45.

Strategies and Communication subscales had 17 units, scoring 4, indicating excellent quality in these areas among the EDIS units the PSTs implemented. Under the ‘good’ rating in the Motivating and Engaging Context and Integration of Science Content subscales, the PSTs’ EDIS units performed particularly well, with 23 and 22 units, respectively.

The overall rating for all PST units revealed a strong inclination towards higher performance, with 23 units rated as ‘good’ and 14 as ‘excellent.’ Fewer PSTs scored at the lower end of the scale, with '0' being almost non-existent across the subscales, suggesting that very few of the EDIS units lacked the fundamental elements altogether. The number of PSTs receiving a '1' was highest in the 'Organization' category, which could indicate a relative difficulty in structuring the EDIS units effectively. Nonetheless, over 80% of the EDIS units implemented were rated as good or excellent under the overall subscale. This indicates that the units were generally effective in meeting the required standards that account for the eight subscales in the curriculum evaluation tool.

The Instructional Strategies subscale received high marks for quality, with 17 of the EDIS units rated as excellent. This suggests that the PSTs successfully employed effective teaching methods conducive to engineering design education. Effective instructional strategies are crucial in engineering design lessons as they provide a structured approach to problem-solving and innovation, directly impacting students' ability to understand and apply engineering concepts. For Teamwork, 17 units were rated excellent, indicating its importance in EDIS instruction and the high emphasis on teamwork in the EDIS units analyzed. Teamwork facilitates the exchange of diverse ideas and promotes collaborative problem-solving, which is essential in engineering tasks where complex problems require multifaceted solutions. Similarly, Communication also had 17 units rated as excellent, highlighting its role in the educational process. In EDIS, communication is vital for articulating problems, proposing solutions, and justifying design choices, fostering a deeper understanding of engineering principles and practices.

These excellent ratings are reflected in the interviews where several PSTs reiterated the importance of these subscales. In their interviews, the PSTs shared several indicators of these three subscales. Alyssa specifically highlighted her use of real-world scenarios as an instructional strategy below and also spoke of striking a necessary balance between science and engineering with the effect of improved student learning:

> "I gave the students a scenario and ours was about food so Cheetos and so we had to figure out what our problem was. So we started with a problem. And from there, I gave them ... so we created the problem as a class 'cause I wanted everybody working on the same problems."

> "Oh for mine I think it great 'cause mine was very ... I think mine was like a good 50/50 of the two because we had pre-taught all the science concepts that we wanted them to learn. And then we applied it through the engineering and so we had taught them like specific heat and energy just the day before. So they kind of understood it, but they didn't. And so using

> the engineering was really nice for them to say oh, we have to use water 'cause we only know it's specific heat."

Alyssa's interview also explains how she prioritized teamwork and effective communication in her EDIS lesson. Here, she describes the initial process of prototype development in her classroom. This requires efficient teamwork and communication to be effective and productive.

> "And then so from there um, they began kind of like thinking about what they would need for their prototype and like sort of starting to create it. And they did that individually so they started creating their prototype. And um I wanted them to work on it individually so that when they all got together, they could discuss it. And so that's what they did after that."

Another PST, Brooke, also shared her informative thoughts and perspectives about the role instructional strategies, teamwork, and communication played in her EDIS classroom implementation. One strategy that stood out was encouraging self-directed learning.

> ... it was kind of the way that I approached in a new way by talking about, like, artificial tissues or synthetic tissues and they didn't quite have any understanding of that and I never really outright told them exactly, um, what it was I wanted them to try to figure it out for themselves what the difference would be between artificial tissues versus real tissues and, like, what were they actually making.

Brooke's interview also provides an understanding of the high excellent ratings for teamwork and communication subscales, especially through her use of step-by-step packets and her allowing students to present their findings. Brooke's creation of packets with checklists can be seen to structure group work, which could foster teamwork by providing clear guidelines and steps for students to follow together. This approach helps ensure that all group members can be on the same page and proceed with a shared understanding of the task at hand. Her inclusion of presentations could encourage students to discuss their results and methods, thereby practicing their communication skills. This also provides opportunities for peer feedback and collaborative discussion.

> "…but I know my students don't always have paper so it's a good way to have and give them a place to write things down so I went through and created a checklist on the front page and created two different packets. Um, one that we were going to do that day in class and one later on, um, when we got into more of the calculations and testing of the prototypes."

> "I mean from an overall ... so I'll focus in on one particular but like an overall thing, I had a lot of interactions with students regarding the consistency of how their tissue turned out and some of them were like- ... mine, there were like couple different things and the students were able to bring this up through their presentations of it too when they were looking at other people's."

Brooke also noticed that through the engineering design process, students were able to reflect on and gain a deeper understanding of science concepts, especially ones they initially struggled with.

> "So I'm happy that I ended up doing it on muscle tissue and it was something that's going to be really applicable to them when we hit the muscular system in a month now after the skeletal system because they already have that idea, oh, this is what muscle's supposed to feel like. This is the elasticity of it, so I think it's something that'll be able to carry them through the rest of the year."

The interviews also provide additional context and perspective on other Phase 2 results. Specifically, question 11, which addresses student struggles, was pertinent to the analyses. The analysis of this interview question produced several insights from the PSTs that revolved around brainstorming/idea generation and engaging students. These reflect the lower frequency of excellent ratings for the motivating and engaging context and the integration of science content categories shown in the table above. This is despite the high frequency of good ratings for these categories. Several PSTs revealed that several students found developing ideas for their projects and activities challenging. According to some, integrating science content to foster individual scientific creativity was a struggle for the students. They observed that students often hesitated to express their ideas, possibly due to fear of judgment or being wrong. This hesitancy impacts how science content is internalized, as active participation and idea generation are crucial for understanding. Elena noted:

> "To me it was coming up with our own individual ideas. A lot of them were like, well I don't know, and were kind of like, scared of, I guess what their crew mates might think."

Rachel and Kiera also provided further perspective below:

> **Rachel**: "I think the brainstorming... they came up with some good ideas as a class but the brainstorming tripped a lot of them up because they were like what are we supposed to brainstorm… how are we supposed to brainstorm?"

> **Kiera**: "I think the individual brainstorming seemed to be the most challenging for them... It's new they immediately wanted to talk to each other... But I think knowing that they were going to be able to discuss it helped them a little bit but I think that was the hardest thing."

Mara noted that some students were less interested in generating multiple project ideas. She observed that her students often wanted to settle on their first idea and resisted considering alternative solutions. This reluctance appeared as a kind of stubbornness to only follow the first idea without exploring other possibilities. Mara had to encourage her students to think beyond their initial concept and consider multiple ideas, which eventually led to a valuable learning experience for the students. They realized that their first idea might not have been the best and recognized the importance of exploring different options before committing to a solution. This reflection and realization were significant for them, as it encouraged a more thoughtful and thorough approach to problem-solving. Below is the excerpt from Mara that support this theme:

> “Uh they hated coming up with ideas. It was so interesting. They definitely just wanted to go with the first idea…. It was the hardest thing. It was definitely ... 'Well they have a great idea we're just going to do that.' And I was like 'No you have to come up with three ideas.' They're like 'No we have one idea it's the best…And a lot of them looked back and said 'Oh yeah our first idea was terrible.' And it was really great (laughs) for them to actually have that reflection.”

The results of the second data analysis phase, utilizing the curriculum evaluation tool by Guzey et al. (2016), highlighted the varied levels of quality in the EDIS units implemented by the PSTs. The high ratings in categories such as Teamwork, Instructional Strategies, and Communication suggest that the PSTs successfully facilitated collaboration, employed effective teaching methods, and encouraged clear communication among students. The predominance of good and excellent ratings in most subscales indicates that most PSTs effectively integrated engineering design into science lessons, creating engaging and motivating learning environments.

However, the thematic analysis of the interviews, specifically focusing on student struggles, reveals underlying challenges. The insights on brainstorming/idea generation and student engagement underscore some of the difficulties faced in fully realizing the potential of the EDIS units. PSTs observed that students often found it challenging to develop their own ideas, indicating a need for more support in fostering individual creativity and confidence in idea generation. This struggle is reflected in the lower frequency of excellent ratings in the Motivating and Engaging Context and Integration of Science Content categories, suggesting that while the overall implementation was successful, there is room for improvement in these areas.

The quotes provide valuable insights into these challenges. They highlight the students' hesitancy to brainstorm and generate ideas independently and their tendency to settle on the first idea without exploring other options. These observations suggest that while the PSTs were generally successful in creating motivating and engaging educational experiences, they also recognized the need to further support students in becoming more comfortable and proficient in the creative aspects of the engineering design process. This understanding is crucial for enhancing the effectiveness of future EDIS units, ensuring that they not only integrate science content effectively but also actively engage and motivate students to think critically and creatively.

Phase 3: Quality of EDIS Implementation

In the third phase of the study, observations of lesson implementations were analyzed to assess the integration of engineering design into science teaching. The observation protocol comprised 30 items spanning two main constructs — the purpose of integration and lesson design and implementation. The analyses revealed that although the PSTs' lessons varied in their adherence to EDIS teaching, almost all (40 out of 45) could be classified as reform-based, with scores above 60 out of 120. Scores across the six subscales—meaning and purpose, design and structure, lesson dynamics, engineering design process (EDP) as a tool, procedural knowledge, and classroom culture—were calculated on a scale of 0-4. The overall EDIS-COP scores ranged from 19 to 110, with 88.89% of lessons scoring above 2 and 62.22% of lessons scoring above 3, indicating a moderate to high level of reformed practice implementation.

Further analysis indicated that the subscale Purpose of Integration (4 items) ranged from 5 to 16, with 95.56% scoring above 2 and 75.56% scoring above 3. This suggests that the majority of the PSTs successfully conveyed the intent behind integrating engineering design into their science lessons. Lesson Design, which encompassed the design and structure of lessons and had five items, ranged from 0 to 19. This subscale had 91.11% of lessons scoring above 2 and 71.11% scoring above 3.

The Implementation subscale itself consists of four subscales that all assess the PSTs' classroom implementation of the EDIS lesson beyond the purpose of integration and lesson design. This subscale ranged from 4 to 77 with 86.67% of lessons scoring above 2 and 62.22% scoring above 3. Similar trends are observed for the four subscales of Implementation. Lesson Dynamics assesses the classroom habits and interactions in the EDIS lesson while Engineering Design Process focuses on the utility of the EDP as a productive tool for meeting learning objectives. Procedural Knowledge addresses the level of science and engineering specific knowledge in the EDIS lessons. This includes scientific questions/engineering problems, using/developing prototypes, mathematical/computational thinking, engaging in evidence-backed arguments, etc. Classroom climate seeks to assess the EDIS classroom based on the student/teacher relationships that were observed. The table below provides further details on how the different subscales scored and shows that more than 80% and 60% of the lessons scored above two and above three, respectively, across all subscales.

The thematic analysis of the interview questions about the PSTs' EDIS science teaching approaches yielded detailed insights. The emphasis was on last eight interview questions

(Appendix B), each aimed at unraveling the nuances of EDIS teaching strategies in the classroom. Table 4 delineates the emergent themes, succinctly capturing the essence and diverse perspectives of the PSTs on the implementation of EDIS.

Table 3: EDIS-COP Classroom Implementation Results

Scales and Subscales (Number of items)	Range		Above Two	Above Three
	Low	High		
EDIS-COP (30)	19	110	88.89%	62.22%
Purpose of Integration (4)	5	16	95.56%	75.56%
Lesson Design (5)	0	19	91.11%	71.11%
Implementation (21)	4	77	86.67%	62.22%
Lesson Dynamics (4)	0	15	84.44%	62.22%
Engineering Design Process (4)	0	15	88.89%	73.33%
Procedural Knowledge (9)	0	34	84.44%	66.67%
Classroom Climate (4)	3	16	93.33%	66.67%

n = 45

Table 4: Emergent Themes from Interviews

Theme Group	Definition
Integrating Engineering into Science	The effective combination of engineering design principles and science content to enhance science learning and engagement.
Student Engagement and Motivation	How engineering design increases student interest, participation, understanding, and motivation in science concepts.
Challenges in Implementation and Conceptualization	Difficulties faced by students and PSTs in applying and understanding engineering design in science lessons.
Practical Application and Real-World Connections	Applying theoretical concepts to real-world scenarios and practical activities to demonstrate the relevance of science.
Educator Reflection and Future Planning	PSTs' self-assessment and thoughts on how to enhance future implementations of engineering design in science education.
Student-Centered Learning and Creativity	Focusing on student-led inquiry, exploration, and encouraging creative problem-solving.
Overcoming Barriers and Enhancing Relationships	Addressing challenges in the educational process, improving student-PST relationships, and overcoming initial skepticism.

The first theme, Integrating Engineering into Science, is enriched by the PSTs' observations that engineering design encourages a deeper engagement with science content. As reflected in Ethan's and Aaron's insights below, this transforms the classroom environment by replacing passive learning with an interactive challenge that fosters a deeper understanding and retention of scientific concepts. Ethan observed the heightened attention to detail in students when learning became an interactive challenge, while Aaron highlighted the lasting impact of applying science in a way that students find memorable and relevant to their daily lives.

> **Ethan**: "I really think that they paid attention to the details because of the fact that it was a design challenge, rather than just a straight-up worksheet where they had the description, and there really wasn't any sort of interactive aspect to it. So, I thought it was really cool."

> **Aaron**: "I think it's a really good way to see applications of science… So I think, with respect to engineering design, um, I really like the application part of it where it's not just students sort of looking at science and going, "Where am I ever going to apply this?" They're looking at it from a new perspective, where they can see how it can be applied in their everyday lives- and see how it's applicable. Give them a more memorable experience, I suppose."

The Student Engagement and Motivation theme reveals that PSTs observed enhanced student interest and motivation in science due to EDIS teaching implementation. Morgan highlighted that students were more engaged with the content and gained exposure to new career possibilities, transforming their perception of engineering. Similarly, Elliot emphasized the positive impact of EDIS on special education students, who showed increased engagement and independent thinking. These insights underscore the value of EDIS in diversifying student perspectives and fostering active participation across diverse learner groups.

Morgan: “Definitely, it got a lot of students more excited about the content that we were covering. It was a totally different perspective than they had ever seen before and opened them up to a lot of different career opportunities maybe they hadn't considered. I feel like engineering is so often talked about, like, you gotta take all the hardest math classes, you've gotta do this, you gotta take all the hardest physics classes. And we were able to show them that like, in an intro bio course, like, they were engineers also.”

Elliot: “Because it was a co-lab class, I noticed that the special education students were really able to engage with this lab… I believe that including elements of engineering design in the lesson was particularly beneficial for these students. It encouraged them to actively participate and think independently.”

The theme highlighting the challenges in implementing and conceptualizing EDIS reflects the unfamiliarity of both teachers and students with this method of science teaching (Banilower et al., 2018; Haag & Megowan, 2015; Yaşar et al., 2006). These challenges, as exemplified by Rachel and Evan, emphasize the complexities and conceptual difficulties students encounter. Rachel noted that her students struggled primarily with understanding the diverse components of their activity and the initial phases of identifying and tackling the problem. Evan observed similar issues, focusing more on students' grasp of the scientific concepts necessary for the activity, highlighting a gap in recalling and applying previously learned concepts in new contexts. This theme underscores the need for more comprehensive preparation and conceptual reinforcement in EDIS teaching methods.

Rachel: “They struggled a lot with this particular activity with kind of the beginning, of not identifying the problem, but just understanding all the pieces of what they were supposed to do … And I think that was just in part because there were a lot of different components … and they didn't really want to read it all at first.”

Evan: “Some [students], they're like, "What's a projectile?" I'm like, "What?" But they kind of knew what it was, but they didn't ... It's like they had forgotten that the rocket- rocket was supposed to simulate a projectile … And I guess I just took it for granted that- that, if I were to ask them about those concepts at a later date, they would refer back to their familiarity with this project--and say, "Oh, yeah. Well, that was just the angle we changed," or, "That was the speed we ... " And I don't know if that happened.”

The theme “Practical Application and Real-World Connections” in the context of EDIS teaching highlights the importance of applying theoretical concepts to real-world scenarios, as described by Hannah and Morgan. Hannah observed that this approach not only fostered deeper critical thinking among her students but also increased their engagement by demonstrating the relevance and significance of the problems they were addressing. Morgan's experience echoed this, noting that their focus on the engineering design process as a problem-solving tool provided students with their first experience of working with living organisms. This practical application helped students understand the unpredictability and flexibility required in science, reinforcing the value of integrating engineering design to make science education more relatable and impactful for students.

Hannah: “I think it just gives more of a real world application of ... I mean there are all these problems--so how would you solve them? It's just a deep, like more critical thinking on their part … With my kids if they don't really see the point behind it--they don't really care and I think this, they were kind of like oh, this is important, this is a big problem. So, I, I think that helped.”

Morgan: “We kind of went about it a different way where like, we were explicitly teaching the engineering design process as a way to problem solve, instead of, um, teaching more like, science concepts through the engineering design process. So, we were a lot more engineering focused. Um, but it, it also provided students with the, their first chance to work with a living organism, um, and see how, like, fickle they can be, um, kind of thing. Um, and I think it was a really good representation of, like, how, I don't know how to say this. Just how, like, in science you can't really predict what's gonna happen and you have to like, be very flexible."

The theme of "Educator Reflection and Future Planning" underscores the importance of PSTs' introspection and prospective enhancements for future EDIS implementations. This theme stems primarily from a question about future EDIS implementation. Mara's reflection on her teaching highlights a desire for improvement, specifically in pre-teaching critical concepts and incorporating more diverse design work. This approach suggests a proactive stance towards enriching student engagement and understanding. Similarly, Claire emphasizes the need for clarity in instruction and terminology, acknowledging the challenges faced and the importance of adapting teaching methods. These insights illustrate the ongoing process of refining teaching strategies to better integrate engineering design in science education, reflecting a dynamic and responsive approach to teaching.

Mara: "I would love to teach this in the future if I can find the funding for it. And I think, like I said before, I would pre-teach biomes a little bit heavier, and hit on the vocab, and hit on different types of biomes, and maybe have them do a little bit more design work,… Like maybe just throw in some more design work into regular class. Then I don't know, if I could figure out a way to have them design different types of biomes, like a desert one with just sand, and like beetles. I think I'd try to do that, have them have an option between like freshwater, and desert, and maybe give a third option too. But yeah, I'd love to do it again."

Claire: "A lot of things. I would change a lot of the directions and the terminology. I think I kind of jumped around from using the term "transport protein" versus "carrier protein," and

> while they're interchangeable I think that tripped the students up a little bit in thinking about it. And in some places, I used simple versus facilitated diffusion, but then in my analysis questions, I just wrote "diffusion and facilitated diffusion." That was honestly because I had to completely learn this all myself. I don't remember any of it.”

The theme “Student-Centered Learning and Creativity” highlights the significance of student-led inquiry and creative problem-solving in EDIS teaching. As observed by Maxwell and Evan, this approach profoundly impacts student engagement. Maxwell notes that giving students control and ownership over their projects, such as a potato experiment, leads to intrinsic motivation and deep involvement. This contrasts with traditional methods, where students might feel they're just completing tasks. Evan reinforces this by describing students' active engagement with physical objects, leading to practical discussions about scientific concepts. This student-led exploration not only enhances understanding but also cultivates a creative and investigative mindset, demonstrating the effectiveness of EDIS in fostering a more dynamic and interactive learning environment.

> **Maxwell**: “Yeah, the biggest benefit is that it really focuses on the student, giving them control and ownership. They take pride in the fact that it's their idea. Unlike other science labs where students might feel they're just checking off boxes, this project makes them genuinely excited. For instance, they'd eagerly anticipate checking on their project, like their potato in fourth block. This intrinsic motivation, coupled with the extended engineering design cycle, allows students to engage deeply with the project over multiple days, reinforcing their enthusiasm and commitment.”

> **Evan**: “I think it was a fantastic way to teach. If I continue teaching, I will absolutely use this project and as many more as I can. Even though I was unsure if they were connecting the concepts as well as they should, they were manipulating a physical object. Their

conversations involved language about air pressure, volumes of liquids, and they were discussing angles. They understood it and what results it should get them. This kind of engagement is hard to achieve just from a lecture."

The theme "Overcoming Barriers and Enhancing Relationships" emphasizes the importance of addressing educational challenges and fostering stronger connections between students and PSTs. Evan's experience highlights the value of supportive feedback and physical presence in enhancing lesson effectiveness and student engagement. The direct impact on student motivation and interest underscores the transformative potential of overcoming initial barriers in EDIS teaching. Morgan's anecdote from a parent-teacher conference reveals the critical need for clear communication of educational objectives. Her proactive response to a parent's feedback demonstrates the significance of making educational purposes explicit, enhancing both student understanding and PST-student relationships. This theme encapsulates the dynamic process of navigating and resolving educational challenges while strengthening the educator-student bond.

Evan: "The assistance I received when [redacted] visited was invaluable. The first time I did this lesson, it was fine. [The] feedback was super good and super helpful … I haven't done assessments yet, but in terms of their engagement, compared to what it normally is, [the students'] interest in being there, and their motivation, it was definitely a lot better."

Morgan: "There was one instance during a parent-teacher conference where a mom mentioned her daughter loves the class but doesn't really know why we're doing it. I realized the need to make the connection more explicit, presenting it as another way to solve problems in science. After that comment, I made sure to be explicit about why we were doing this in class. It was clear in my mind why we were doing it, but I hadn't communicated that effectively."

The synthesis of themes in this study paints a comprehensive picture of the PSTs' journey in integrating engineering design into science teaching. The themes interweave to create a narrative of progress, challenges, and aspirations. The initial step of integrating engineering principles in science teaching, highlighted by Ethan and Aaron, sets the stage for an interactive and memorable learning experience. This transformation extends into student engagement and motivation, as noted by Morgan and Elliot, where students' perspectives on science and engineering are broadened, and special education students find new ways to engage. However, this journey is not without its challenges. As Rachel and Evan's experiences show, conceptual hurdles and complexities in implementing EDIS underscore the need for more robust preparation and reinforcement in teaching methods.

The themes of practical application and real-world connections, as reflected in Hannah and Morgan's insights, emphasize the importance of bridging theoretical concepts with tangible, real-life scenarios. This approach not only deepens critical thinking but also heightens student interest and involvement. Additionally, the theme of educator reflection and future planning, highlighted by Mara and Claire, reflects an ongoing process of introspection and improvement in teaching strategies. This proactive adaptation is crucial for enriching student engagement and understanding in EDIS.

Moreover, Maxwell and Evan's observations on student-centered learning and creativity underscore the value of fostering an environment where students lead their inquiry and creatively solve problems. This approach enhances student involvement and cultivates a more dynamic learning atmosphere. Finally, overcoming barriers and enhancing relationships, as experienced by Evan and Morgan, reveal the transformative potential of addressing educational challenges and fostering stronger connections between students and teachers. This theme captures the essence of navigating and resolving educational challenges while strengthening educator-student relationships. Together, these themes weave a narrative of growth, reflection, and persistent evolution in the realm of EDIS teaching, underscoring the dynamic and responsive nature of this educational approach.

Collated Data Analysis

To comprehensively assess the integration of engineering design in science teaching, data from all analysis phases were aggregated and scrutinized for trends. This approach aimed to better understand the effectiveness of PST EDIS implementation throughout the study. Classroom observations with scores above 60 were delineated from those with scores lower than 60. In the quality analysis of the EDIS units, scores of 3 and 4 indicated high quality, a score of 2 signified medium, and a score of 1 indicated low quality. The categorization of EDIS units into Innovation, Adaptation, and Application remained unchanged. Table 5 presents the eight identified patterns and their frequencies within the dataset. Based on the information in the table, focus and further analysis were placed on the two most frequent patterns.

Table 5: Results from Whole Data Analysis

ID	Implementation	Quality	Categorization	Number of PSTs
1	Above 60	3 & 4	Innovation	23
2	Above 60	3 & 4	Adaptation	14
3	Above 60	2	Innovation	1
4	Above 60	2	Adaptation	2
5	Below 60	2	Adaptation	1
6	Below 60	2	Innovation	1
7	Below 60	1	Innovation	1
8	Below 60	1	Adaptation	2

The analysis indicates a prominent trend where the most effective EDIS implementations were those categorized as 'Innovation' with high-quality scores and reformed classroom implementation (above 60). This pattern accounted for 51.1%, suggesting that when PSTs leveraged originality and creativity in their engineering design integration, the quality of the lesson improved significantly. Adaptation strategies also demonstrated success, with 31.1% where PSTs effectively incorporated modifications from sources other than the science methods course. This pattern included high-quality EDIS units and reformed classroom implementation. This pattern suggests that PSTs can adeptly tweak and refine their science teaching to include engineering design integration while maintaining high-quality EDIS units.

These results reveal a clear order in the frequency of different patterns from the PSTs' EDIS unit implementation. Well-implemented, high-quality, and Innovative EDIS units, constituting over half of the observed implementations, were the most frequent. The second most frequent pattern of adaptative EDIS units, high-quality units, and reformed classroom implementation made up just under one-third of the data. Collectively, these patterns suggest that while innovative units were most prevalent among instances of reformed EDIS implementation, adaptation units were still well represented. This provides some insight into the diverse potential available to PSTs seeking to integrate EDIS teaching into their science teaching repertoire.

Discussion

This study reported on how science PSTs participating in an intervention driven by situated learning theoretical framework (McLellan, 1996) learned and used EDIS instruction in schools during their student teaching experiences. Concerning the planning and implementation of EDIS lessons, the results indicate that the majority of PSTs involved in this study produced high-quality units and implemented their EDIS lessons in a way analogous to reformed practice standards. This is apparent from the results where over 80% of the EDIS units under the overall subscale in phase 2 analysis were rated as either good or excellent. This trend is mirrored in the analysis of EDIS classroom implementation, where about 60% of the lessons scored more than 3, and over 80% of the lessons scored more than 2. The prominence of the Innovation pattern aligns closely with the intervention's goals. This innovative approach adopted by PSTs underscores the necessity for creativity in STEM education and demonstrates a commitment to enhancing student engagement and learning outcomes. It reflects the evolving landscape of science education, where traditional methodologies are being augmented with dynamic and interactive teaching practices.

Comparing these findings with existing research, parallels and deviations emerge. Studies like Capobianco and Rupp (2014) and Boesdorfer (2017) highlight a common theme: the gap between planning and actual classroom implementation of engineering design. These works point to initial strengths in planning and intention but reveal difficulties in fully executing integrated engineering design in practice. The results of this study diverge from those of Capobianco and Rupp (2014) and Boesdorfer (2017) in that it indicates that the EDIS intervention designed on a situated learning framework can provide better alignment between planning and classroom implementation of engineering design lessons. Guzey et al. (2019b) reinforce this trend, indicating that understanding engineering design principles does not always translate into effective classroom application. This recurring pattern underscores the complex nature of integrating such innovative practices, heavily influenced by variables such as teacher experience and pedagogical training. This study further suggests that these influential variables, under the right intervention and framework, can potentially lead to an improved understanding of engineering design principles and effective classroom implementation. The results of this study diverge from those of Capobianco and Rupp (2014) and Boesdorfer (2017) in that it indicates that the EDIS intervention designed on a situated learning framework can provide better alignment between planning and classroom implementation of engineering design lessons.

This study's findings on innovation and adaptation echo the broader incentive for more creative approaches in science education. Previous research has consistently highlighted the importance of innovative teaching methods in fostering deeper understanding and engagement among students (e.g., Alejandro & David, 2018; Ferrari et al., 2009). The alignment between these patterns and the literature reinforces the critical role of creativity in effective science education. The adaptation pattern identified in this study suggests a pivotal role for flexibility in teaching. The PSTs' ability to modify existing lesson plans for engineering design integration speaks to the adaptive nature of effective teaching. This approach not only allows educators to tailor their lessons to specific classroom needs but also demonstrates a practical application of theoretical concepts, aligning with contemporary educational standards and student expectations. It also exemplifies educators' understanding of engineering principles and how to effectively integrate them into existing inquiry activities and curricula, further enriching the teaching and learning experience.

The absence of the Application category among the EDIS units in this study is intriguing and can be attributed to several key aspects of the teacher preparation program. PSTs were required to design lessons as part of their curriculum, which naturally incentivized them to move beyond mere application of learned concepts. This requirement fostered an environment where creativity was encouraged and necessary for meeting the academic expectations set forth. Additionally, the cognitive apprenticeship model adopted within the situated learning framework of the study provided continuous feedback and guidance. This mentoring approach enhanced the PSTs' capacity to critically engage with and innovate upon the engineering design principles taught rather than simply applying them as is. This model of instruction and feedback effectively supported PSTs in developing more dynamic and contextually tailored educational strategies, which is why purely application-based units were notably absent in the analyzed data.

Regarding replicability in other contexts, the unique composition of the expert team in this study significantly contributed to the PSTs' success in creating innovative and adaptable EDIS units. The team included a seasoned engineer with extensive experience in university-level engineering education and direct involvement with K-12 outreach, a faculty member skilled in undergraduate engineering education, and an expert in the pedagogical applications of engineering teaching methods. This combination of expertise provided a robust support system for the PSTs, enriching the developmental process of their EDIS units. However, this unique assembly of experts raises questions about the replicability of the study's results in other settings where such specialized knowledge and support may not be readily available. The success seen here might be challenging to duplicate in environments lacking similar expert resources, which could affect the feasibility of widely implementing this teacher preparation model.

The application of situated learning theory in the context of PSTs innovating and adapting their EDIS lessons reveals a harmonious intersection of theory and practice. This framework, emphasizing contextually and collaboratively embedded learning, is evident in the PSTs' approach to developing and implementing EDIS lessons. The situated learning framework posits knowledge as a product of activity within specific contexts. In this study, PSTs engaged in EDIS within their classrooms' authentic environments, facilitating the development of practical knowledge that encouraged innovative and adaptive teaching methods. Central to situated learning is cognitive apprenticeship, where learners observe and emulate expert practices. This method was evident in the study as PSTs observed and learned from expertly modeled EDIS teaching methods. The intervention's emphasis on the Framework for K-12 Science Education (NRC, 2012) and the NGSS (NGSS Lead States, 2013) provided a solid foundation for PSTs to apply these methodologies innovatively in their classrooms.

Consistent with situated learning, the intervention offered PSTs numerous opportunities to practice EDIS, enhancing their understanding and application of these methods. This repeated practice, supported by scaffolding from instructors, contributed to their ability to innovate in their instructional approaches. Collaboration and reflection, crucial elements of situated learning, were integral to the intervention. PSTs worked with instructors, mentors, and peers, fostering a collaborative learning environment that encouraged reflection and collective problem-solving, leading to innovative EDIS approaches. Finally, the integration of these learning principles during PSTs' student teaching further solidified their ability to adapt and innovate EDIS teaching methods. The supportive, collaborative, and reflective environment of the seminar course played a pivotal role in this process, demonstrating the effectiveness of the situated learning model in teacher education.

Implications

In the context of this study, several practical, curricular, and policy implications can be discerned. The findings in this study underscores the importance of training teachers in innovative and adaptive lesson planning. This training should focus on equipping teachers with skills to integrate engineering design into science instruction, thereby enhancing student engagement and learning. Emphasis should be placed on hands-on, creative approaches that align with current educational standards and practices. The findings advocate for the development of curriculum materials that incorporate engineering design into science teacher education and schools. Such materials should be designed to facilitate the seamless integration of engineering concepts with science topics. This approach can enhance students' understanding of both disciplines, fostering a more comprehensive and applied learning experience.

There is a clear need for policy initiatives that support and fund innovative teaching methods, particularly those involving the integration of engineering design in science instruction. Investment in resources, professional development programs, and educational tools that facilitate such teaching methods can significantly impact the quality of science education. These implications highlight the necessity of a collaborative approach involving educators, curriculum developers, and policymakers to effectively implement and sustain innovative teaching strategies in science education. The goal is to create a more engaging, applicable, and integrative learning environment for students, preparing them for the challenges of the modern world.

Limitations

The study's generalizability is constrained due to the small number of participants and being conducted in a single geographical area. This raises questions about the applicability of the findings to broader, more diverse educational contexts. The specific educational setting and the duration of the EDIS intervention were unique to this study. These factors limit the ability to generalize the findings to different educational environments or to long-term implementations. The study relied heavily on observational scoring and interviews of PSTs, which may introduce biases. Such methods could lead to discrepancies between perceived classroom practices and actual classroom practices. These limitations highlight the need for additional research with varied sample sizes, diverse populations, and different educational contexts to strengthen the reliability and applicability of the findings.

Conclusion

This study demonstrates the effective implementation of EDIS by PSTs in their student teaching. It highlights the significant embrace of engineering design in teaching practices, aligned with reform-based instructional strategies. The teacher preparation program played a crucial role in this integration, fueled by PSTs' intrinsic motivation to enrich science instruction with engineering concepts. The study presents a comprehensive analysis of the implementation, categorization, and quality of EDIS units, alongside the challenges faced, underscoring the complexities and effectiveness of integrating engineering design into science education. Our findings suggest the significant role that innovative teaching methods play in enhancing PST implementation of engineering design. The positive strides through the EDIS intervention underscore the necessity for teacher education programs to focus on training that fosters adaptive and creative lesson planning. This study contributes valuable insights into curriculum development and policy implications in science education. This research highlights the need for continued exploration and refinement in the integration of engineering design in science classrooms, paving the way for future studies that could further expand our understanding of integrated science and engineering education.

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Appendix 1

Engineering Design Integrated Science Classroom Observation Protocol (EDISCOP)

1. Background

Name of the teacher____________________ Teaching certification________

Teaching experience (years/months) _______ School district________

Class observed_____________________ Subject observed______________

Observer_________________________ Date of observation__________

Start time: ______________________ End time__________________

2. Contextual Background & Activities

In the space below, give a brief description of the lesson observed, the classroom setting in which the lesson took place (space, seating arrangements, etc.), and any relevant details about the students (number, gender, ethnicity) and teacher(s), that you think are important and useful in data interpretation. Use diagrams if they seem appropriate.

Record here events that may help in documenting the ratings.

Time	Description of events

Construct	Subscales	Guiding Questions & Items	Scoring				
			Not Evident	Limited Evidence	Neutral/Not Sure	Evident	Very Evident
Purpose of Integration	*Meaning & Purpose*	**Guiding Question**: How does the integration of engineering design enhance the meaning and purpose of the science lesson?					
		Engineering design process enabled students to learn science in ways not otherwise possible.	0	1	2	3	4
		The use of engineering design strengthened students' conceptual understanding of science.	0	1	2	3	4
		The lesson promoted engineering design understanding among students.	0	1	2	3	4
		Developing engineering design solutions/prototypes as the way to understand and explain scientific phenomena was a majority priority in this lesson.	0	1	2	3	4
Lesson Design	*Design & Structure*	**Guiding Question**: What are the essential elements of an engineering design integrated science lesson?					
		Engineering design process was integrated into the lesson, as opposed to being a separate curricular focus.	0	1	2	3	4
		The introduction of engineering design had a "just in time" characteristic that propelled the lesson.	0	1	2	3	4
		The use of engineering design was directly related to the analysis or interpretation of real-world science phenomena.	0	1	2	3	4
		The lesson was designed to engage students as members of a learning community	0	1	2	3	4
		The lesson was designed for student exploration to precede formal presentations/communication.	0	1	2	3	4
Implementation	*Lesson Dynamics*	**Guiding Question:** What classroom habits exist in an engineering design integrated science lesson?					
		Engineering design process was the process of negotiation involving students as well as the teacher.	0	1	2	3	4
		In this lesson, there were moments when students became excited about the ways engineering design was contributing to their understanding and enjoyment of science.	0	1	2	3	4
		Students frequently used engineering design prototypes to communicate or clarify scientific ideas with the teacher, other students, or just with themselves.	0	1	2	3	4
		The use of engineering design in this lesson was open to critique.	0	1	2	3	4
	Engineering design Process as a Tool	**Guiding Question**: Is engineering design process utilized as a productive tool to complete learning objective(s)?					
		Students used engineering design process to explore connections among variables.	0	1	2	3	4
		Engineering design process was the fundamental tool used by students to address scientific question or problem in the lesson.	0	1	2	3	4
		Students often used engineering design to help make their thinking more precise.	0	1	2	3	4
		The teacher often encouraged students to use engineering design process to support the reasonableness of their argumentation.	0	1	2	3	4
	Proc	**Guiding Question:** What procedural knowledge exists in					

		engineering design integrated science lesson?					
		Students were engaged in scientifically oriented questions (science)/problem (engineering).	0	1	2	3	4
		Students were engaged in developing and using models/prototypes.	0	1	2	3	4
		Students planned and carried out investigations.	0	1	2	3	4
		Students were engaged in analyzing and interpreting data.	0	1	2	3	4
		Students used mathematics and computational thinking.	0	1	2	3	4
		Students were engaged in constructing explanations (for science) and designing solutions (for engineering).	0	1	2	3	4
		Students were engaged in argument from evidence.	0	1	2	3	4
		Students were engaged in communicating science concepts and design solutions.	0	1	2	3	4
		Students were engaged in cross-cutting concepts.	0	1	2	3	4
	Classroom Culture	**Guiding Question:** What communicative and student/teacher relationships exist in engineering design integrated science lesson?					
		There was a climate of respect for what others had to say.	0	1	2	3	4
		Students worked in collaborative groups.	0	1	2	3	4
		The teacher acted as a resource person, working to support and enhance student learning.	0	1	2	3	4
		There was a high proportion of student talk and a significant amount of it occurred between and among students.	0	1	2	3	4

Some Items Adapted from RTOP & MISCOP

Continue recording events here that may help in documenting the ratings.

Time	Description of events

Write below additional comments you may wish to make about this lesson

Appendix 2

Engineering Design Process Implementation Interview Questions (30 minutes) ---
Implementation of the engineering design process and engineering practices in NGSS

<u>General Engineering Design Process Knowledge Questions</u>

1. How do you describe engineering?

2. How do you describe engineering design?

3. Please, walk me through the engineering design process that you taught in your classroom. ***(Ask them to draw a picture).*** How is this process similar to or different from the one that you learned about in your methods course?

4. What does integrating engineering design into science teaching mean to you?

5. How would you describe the following: ***(I can show them their pre and post results)***
    a. Defining a problem in engineering?
    b. Designing engineering solutions?

<u>Engineering Design Process Implementation Questions</u>

6. To what extent did the lesson proceed as planned?

(The following questions are about the pre-service teachers' perceptions of how the lesson was actually taught, and not how it was planned.)

7. How well do you think engineering design was incorporated into the science content?

8. How (if at all) do you think engineering design helped the students better learn the science content in your specific lesson?

9. Please give an example of an interaction that you had with a student about their prototype.

10. What are some of the benefits of incorporating engineering design into science classrooms?

11. In your opinion, what component of the engineering design process did students struggle with the most?

12. If you were to teach this lesson in the future, what (if anything) would you do differently?

13. Is there any additional information that you would like for us to know about your experience teaching engineering design in the classroom?

Appendix 3

STEM Integration Curriculum Assessment (STEM-ICA)

Overview: The rubric is for the evaluation of STEM integration curriculum. Elements of quality were identified in a literature review and analysis of the national and state level education standards. These quality indicators summarized and mapped to the rubric categories. There are nine separate rubric categories; however, they are closely related and connected to each other. There are two types of ratings: specific and overall.

The SPECIFIC RATINGS should be done first – Reviewers are asked to answer some yes or no questions, provide a rating of quality, and give evidence to support the ratings. Reviewers will answer the questions first by marking no, somewhat, or yes for each item. They are intended to help reviewers reflect on specific elements of the curriculum unit and to help them understand the intent of the rubric question. They are meant to be representative of some important elements but not inclusive of all.

The second item is an OVERALL RATING – This is a summary assessment of the effectiveness of the curriculum unit in helping students learn the knowledge and skills and/or practices identified in national and state level education standards. Reviewers are asked to provide both a rating and the evidence to support the rating.

Rating Scale: All items are rated on a 5-point scale from 0-4 describing the extent to which the unit meets the characteristics.

- 0 = not present – none of the characteristics described in the question are reflected in the curriculum unit.
- 1 = weak
- 2 = adequate
- 3 = good
- 4 = excellent – all of the characteristics described in the question are reflected in a material.
- NA/DK – These should be used in rare circumstances.

SPECIFIC RATINGS – Please answer the Yes or No questions first by marking yes, somewhat or no for each item before answering the rubric questions.

1. A Motivating and Engaging Context

Does the Curriculum Unit….		**No**	**Some what**	**Yes**
Allow students to make sense of the situation based on extensions of their own personal knowledge and experiences? Can students reasonably bring prior knowledge? Can students bring multiple perspectives to this?				
Engage and motivate students from different backgrounds? Typically, this is going to be somewhat.				
Provide a context with a compelling purpose (what, why, and for whom)?				
	Include global, economic, environmental, and/or societal contexts? Need to have explicit connections or cost constraints			
	Include current events and/or contemporary issues?			
Provide opportunities to apply engineering process in partially or completely realistic situations?				

- To what extent does the curriculum unit use a motivating and engaging context?
  NA/DK 0 1 2 3 4

- Describe the evidence that supports your ratings:

2. An Engineering Design Challenge

Does the Curriculum Unit….	**No**	**Some what**	**Yes**
Contain activities that require students to use engineering design processes?			
Address design elements of problem, background, plan, implement, test, evaluate (or other similar representation of the processes of design)?			
Allow students opportunities to learn from failure/past experiences? Present in redesign			
Allow students to redesign?			
Contain an engineering challenge that includes a client?			
Allow students to participate in an open-ended engineering design challenge in which they design and assess processes or build and evaluate prototypes/models/solutions?			
Contain an engineering challenge that requires students to consider constraints, safety, reliability, risks, alternatives, trade-offs, and/or ethical considerations?			
Promote engineering habits of mind (e.g. systems thinking, creativity, perseverance)?			
Requires students to explore or develop technologies (e.g. bridges, water filters, recycling plant processes) from the field of engineering (e.g. civil engineering, environmental engineering, industrial engineering) discussed in the engineering challenge?			
Promote understanding about what engineering is and what engineers do at work?			

- To what extent does the curriculum unit allow students to learn engineering design by integrating an engineering design challenge?
  NA/DK 0 1 2 3 4

- Describe the evidence that supports your ratings:

3. Integration of Science Content

Does the Curriculum Unit….	No	Some what	Yes
Address state standards in science at levels that match test specifications and beyond?			
Integrate science concepts that are grade level appropriate?			
Require students to learn, understand, and use fundamental science concepts and/or big ideas of science necessary to solve the engineering challenge?			
Promote coherent conceptual understanding of science?			
Provide opportunities to learn and implement different techniques, skills, processes, and tools related to science learning?			

- To what extent does the curriculum unit integrate science content that are needed to solve the engineering challenge and support in-depth understanding?
  NA/DK 0 1 2 3 4

- Describe the evidence that supports your ratings:

5. Instructional Strategies

Does the Curriculum Unit….	**No**	**Some what**	**Yes**
Contains lesson and activities that are student-centered – minds-on and/or minds-on/hands-on?			
Contain some activities that require students to collect and analyze information or data before arriving at a solution?			
Embed argumentation as a strategy to teach engineering and/or science (often data and data analysis provides the evidence for claims made)? Argumentation using data to support your claims.			
Include explicitly connections to the overall design challenge/context in every lesson so that students understand why each lesson is important?			
Involve students in activities that embed STEM ideas to be learned in multiple modes of representation (real life situation, pictures, verbal symbols, written symbols, manipulatives) with an emphasis on translations within and between modes? Students can represent their knowledge in various modes (i.e. drawing pictures, creating a prototype)			

- To what extent does the curriculum unit support student centered teaching strategies? NA/DK 0 1 2 3 4

- Describe the evidence that supports your ratings:

6. Teamwork

Does the Curriculum Unit….	**No**	**Some what**	**Yes**
Require students to collaborate with others?			
Include opportunities for students to demonstrate individual responsibility while working in a team? As a team --- not just turning in stuff			
Build in instructional strategies that encourage positive team interactions and the five elements of cooperative learning? Intentionally encouraging each person to talk			
Require that each member of the team is needed for completion of the activities/tasks?			

- To what extent does the curriculum unit enable students to develop teamwork skills?
  NA/DK 0 1 2 3 4

- Describe the evidence that supports your ratings:

7. Communication

Does the Curriculum Unit….	**No**	**Some what**	**Yes**
Require students to communicate science concepts (e.g. oral, written, or using visual aids such as charts or graphs)?			
Require students to communicate engineering thinking/engineering solutions/products (e.g. oral such as presentation to the client, written such as a memo to the client, technical communication, or with visual aids such as schematics)? Need to have some actual communication			
Encourage multiple modes of representation (real life situations, pictures, verbal symbols, written symbols, manipulatives/concrete models) within communication of learning? Create a prototype and write about or talk about it			
Include a requirement for argumentation strategies?			

- To what extent does the curriculum unit enable students to develop communication skills in science, mathematics, and engineering?
  NA/DK 0 1 2 3 4

- Describe the evidence that supports your ratings:

8. Performance and Formative Assessment

Does the Curriculum Unit….	**No**	**Some what**	**Yes**
Are closely aligned with the learning objectives and goals and content from the multiple disciplines of STEM? KUDs and learning objectives			
Are tied meaningfully to state standards and test specifications and, when possible, go beyond these specifications? State standards			
Provide students opportunities to produce evidence of understanding and abilities in different ways through performance tasks?			
Provide guidance to the teacher that could be used to improve implementation of the curriculum unit? Improvement for future use			

- To what extent do the assessments and required assignments in the curriculum unit measure students' knowledge and skills?
  NA/DK 0 1 2 3 4

- Describe the evidence that supports your ratings:

9. Organization

Does the Curriculum Unit….	**No**	**Some what**	**Yes**
Present clear objectives and learning goals from the multiple disciplines of STEM that are tied meaningfully to state standards, and when possible, go beyond these specifications? The standards need to be both science and engineering design --- do the learning objectives tie to the state standards – is there some coherence			
Include activities/lessons that flow in a logical and sequential order so they build on each other?			
Provide guidance and instructional strategies for teachers who are unfamiliar with the unit?			

- How well is the curriculum unit organized?
  NA/DK 0 1 2 3 4

- Describe the evidence that supports your ratings:

OVERALL RATINGS – Please rate the effectiveness of the curriculum unit in having students learn the knowledge and skills and/or practices identified in national and state education standards. Review the learning objectives of the curriculum once again before describing the evidence that supports your conclusions. This description is not intended to be an average of all the previous ratings, but your overall judgement of quality and likely impact of the curriculum unit. Please describe the evidence that supports your conclusions in the space provided.

- To what extent will the curriculum unit help students learn appropriate grade level knowledge, skills and/or practices of STEM subjects as identified in the national and state education standards?

  NA/DK 0 1 2 3 4

- Describe the evidence that supports your ratings: