THE IMPACT OF PRE-SERVICE SCIENCE TEACHERS' IMPLEMENTATION OF ENGINEERING DESIGN INTEGRATED SCIENCE TEACHING ON STUDENT LEARNING OUTCOMES

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ABSTRACT

The purpose of this sequential explanatory mixed methods study was to examine the impact of engineering design integrated science (EDIS) instruction student learning outcomes in both science and engineering design. The implementation of the study and interpretation of the results were guided by the Opportunity to Learn (OTL) theoretical framework (Kurz, 2011), which says that student learning is impacted by the opportunities provided to students to learn the curriculum. The OTL framework has three main dimensions – *content coverage, quality, and time*.

Participants were nine secondary science pre-service teachers, and 460 high school students, who received EDIS instruction from the pre-service teachers. First, pre-service science teachers learned about engineering design and how to plan for and teach EDIS units in their science methods course. Then, they implemented their EDIS units in high school classrooms during their student teaching placements.

Prior to and following the EDIS units, high school students completed three assessments to measure their science knowledge, understanding of engineering design, and their perceptions of engineering design. Students responses were coded by two researchers, and the psychometrics of the instruments were analyzed using measure of reliability and validity, including factor analysis. Pre-service teachers' unit plans were analyzed for the three components of OTL using pre-established rubrics. The pre-service teachers were then divided into two groups, high and low OTL environments, based on their OTL scores. A multiple regression analysis was then performed to determine if there were differences in student learning outcomes across the two learning environments.

In an effort to better understand possible explanations for student learning gains, an exemplar EDIS instruction was selected based on specific criteria. Next, a thick rich description of the instructional planning and implementation of the exemplar EDIS unit was provided through qualitative analysis of the unit plan and lesson observation field notes. Then, a qualitative analysis of student reflections and the pre-service teacher interview resulted in themes of possible explanations for the student learning gains found in the quantitative results. These themes were then supported by observation data.

Results indicate that across all classrooms, students demonstrated a statistically significant increase in their knowledge of science content, understanding of an engineering design process, and their perceptions of engineering design, following EDIS instruction. Furthermore, a high OTL environment was beneficial for students, who performed low on the science content and engineering design content tests before instruction. The exemplar EDIS unit provided a "high" OTL environment with a high degree of content coverage, quality of instruction, and time on unit. Students in the exemplar EDIS unit scored the lowest on the pre-assessments as compared to other classes, yet they had some of the highest post-assessment scores. Results from the qualitative analysis of the exemplar class suggest that the following four elements served as potential explanations for student learning outcomes: (1) the visualization provided by the models; (2) the hands-on building and creating of prototypes; (3) the opportunity for students to learn from mistakes through the redesign phase; and (4) the chance that students had to brainstorm and express their creativity.

Overall, the results show that engineering design integrated science instruction positively impacts student learning in science and engineering design and their perceptions of engineering design. Results also show that instructional planning and implementation factors help explain student learning outcomes in EDIS environment. Additionally, model visualization, prototype building, redesigning, and brainstorming influenced student learning. Although the results cannot be generalized, these findings have implications for researchers, science teacher educators, and teaching and learning of engineering design and science instruction in schools.

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APPROVAL OF THE DISSERTATION

This dissertation, "The Impact of Pre-Service Science Teachers' Implementation of Engineering Design Integrated Science Teaching on Student Learning Outcomes", has been approved by the Graduate Faculty of the Curry School of Education in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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DEDICATION

To my parents, Mark and Kathryn Ochs,
who taught me to “love the game beyond the prize.”

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CHAPTER 1: INTRODUCTION

Problem Statement

Current science education reform documents, *The New Framework for K-12 Science Education* (National Research Council [NRC], 2012) and the *Next Generation Science Standards* (NGSS) (NGSS Lead States, 2013) emphasize science and engineering design integration in science classrooms. *The Framework for K-12 Science Education* was created as a guide for the development of the NGSS. Within both documents, there are three dimensions namely: *science and engineering practices, disciplinary core ideas, and cross-cutting concepts.* As such, teachers are expected to teach all three dimensions in their science classrooms. This includes engineering, which is defined by the *New Framework for K-12 Science Education* as "any engagement in a systematic practice of design to achieve solutions to particular human problems" (p.11).

Of note within the reform documents are the eight science and engineering practices, which were developed to mirror the practices of scientists and engineers. These practices are: (1) Asking questions (for science) and defining problems (for engineering); (2) Developing and using models; (3) Planning and carrying out investigations; (4) Analyzing and interpreting data; (5) Using mathematics and computational thinking; (6) Constructing explanations (for science) and designing solutions (for engineering); (7) Engaging in argument from evidence; and (8) Obtaining, evaluating and communicating information.

The science and engineering practices are presented in such a way that suggests a high degree of overlap between science and engineering and offers the potential for addressing both content areas simultaneously. Addressing the content areas concurrently is further supported through the NRC's definition of engineering design (ED) as "an iterative cycle of design that offers the greatest potential for applying science knowledge in the classroom and engaging in engineering practices" (NRC, 2012, p.201-202). The engineering design process (EDP) can serve as a way to incorporate engineering design into science curriculum (NRC, 2012, p.201). Throughout the study, reference is made to the engineering design process. For the purposes of this study, one EDP model has been selected. However, it should be noted that this is not the only EDP model and that many other EDP models exist. Additionally, in this study, the term "engineering design integrated science" (EDIS) will be used to refer to the teaching of science content and practices through the use of engineering design.

The NRC's justification for the introduction of engineering design into K-12 science classrooms is based on the following five potential student learning benefits: (1) Improved learning and achievement in science and math; (2) Increased awareness of engineering and the work of engineers; (3) Understanding of and the ability to engage in engineering design; (4) Interest in pursuing engineering as a career; and (5) Increased technological literacy (NRC, 2009, p.49-50). Additional justifications for the integration of engineering design into science instruction are that engineering activities can leverage students' natural curiosity to assist in learning specific content (Brophy, Klein, Portsmore, & Roger, 2008), enable students to solve problems in science (Kolodner, 2002), and may appeal to traditionally underrepresented student population and provide them with opportunities for innovation (Mendoza Diaz & Cox, 2012).

Although current science education reforms (e.g. NRC, 2012; NGSS Lead States, 2013) call for the integration of engineering design into science classrooms, many unanswered questions remain about the impact of EDIS instruction on student learning outcomes and the factors that may influence student learning in such an environment. In this study, student learning outcomes refers to student achievement in science and engineering design and student perceptions of engineering design. Although, researchers have implemented instruction that integrates engineering design and science, most studies have focused on assessing student learning outcomes in only one content area - either science or engineering design. In general, such studies have reported increased student learning outcomes in science (Marulcu & Barnett, 2013) and in engineering design (Crotty, Guzey, Roehrig, Glancy, Ring-Whalen, & Moore, 2017). On the other hand, studies that have measured both science and engineering design student learning outcomes have provided mixed results (e.g. Apedoe et al., 2008; Guzey, Moore, Harwell, & Moreno, 2016b). For example, Apedoe et al. (2008) found that after high school chemistry students were exposed to an engineering design unit, they demonstrated greater learning gains in both their chemistry content knowledge and their interest in engineering careers, as compared to a control group. Conversely, Tran and Nathan (2010) found that exposure to an integrated engineering, science, and math curriculum resulted in smaller science achievement gains for students, as compared to those students not participating in the curriculum. According to NGSS, an integrated lesson is one that addresses both science and engineering design in the instruction, and therefore students should be assessed in both content areas. However, very few studies assess student learning outcomes in both science and engineering design (e.g. Apedoe et al., 2008; Selcen Guzey, Moore, & Morse, 2016).

In addition, there is lack of research on the effect of teacher factors on student learning outcomes in EDIS instruction. In the current study, teacher factors refer to the broad category of elements that occur at the teacher or classroom level that all students, in a classroom with a particular teacher, would have the same exposure to. Such teacher level factors may occur during instructional planning (e.g. quality of the unit plan) or during the implementation of the unit (e.g. instructional strategies used). In the few studies that have addressed teacher factors, researchers suggest that both the degree to which teachers integrate science and engineering design (Crotty et al., 2017; Guzey, Harwell, Moreno, Peralta, & Moore, 2017a) and the way that teachers implement the lesson (Dare, Ellis, & Roehrig, 2014) may influence student learning outcomes. For example, Crotty et al. (2017) reported that an explicit integration of the content – when science concepts are taught through engineering design – can lead to better student learning outcomes as compared to other integration models. However, existing literature provides little insight into how teacher factors have an impact on student learning outcomes in EDIS instruction. Yet, science education research shows that teacher factors can influence student learning outcomes in other instructional strategies, such as inquiry (Blanchard, Southerland, & Granger, 2009; Capps, Crawford, & Constas, 2012).

A review of the literature also shows that most studies have focused on in-service teachers' implementation of engineering design in science classrooms (e.g. Dare et al., 2014; Wendell & Rogers, 2013). There is a lack of research on pre-service teachers' implementation of EDIS instruction in schools during their clinical or field experiences.

In light of the above gaps in the literature on EDIS instruction, there is a need for more research in the following three areas: (1) the impacts of EDIS instruction on student learning outcomes in both science and engineering design, (2) the factors that impact student learning outcomes, and (3) studies that include pre-service science teachers. In order to begin addressing these gaps, our science teacher education program trained pre-service science teachers in developing and teaching EDIS units in schools. This study examined the extent to which pre-service teachers' development and implementation of EDIS units in schools impacted student learning outcomes in both science and engineering design.

Purpose

The purpose of the current study was two-fold. First, to measure students' science content knowledge, understanding of the engineering design process, and their perceptions of engineering design before and after engineering design integrated science instruction. Second, to identify teacher instructional factors at both the planning and implementation phases that may impact student outcomes in engineering design integrated science instruction.

Research Questions

The current study addressed the following research questions:

1. To what extent does engineering design integrated science instruction, situated in an OTL model, impact student learning outcomes in science (as measured by science content knowledge) and engineering design (as measured by understanding of engineering design and perceptions of engineering)? *(Quantitative)*
2. To what extent does the qualitative data (unit plan, classroom observations, student responses & teacher interview response) from an exemplar of EDIS instruction, within a high *Opportunity to Learn* environment, help to explain the quantitative results of student learning outcomes? *(Qualitative)*

Rationale & Significance of Study

National science education reform documents (e.g. NRC, 2012; NGSS Lead States, 2013) call for the incorporation of engineering design into science instruction. Although there is an increase in the number of teachers attempting to implement engineering design in their science classrooms (Carr, Bennett, & Strobel, 2012), many questions still remain about engineering design integrated science instruction. For example, while the NRC (2009) puts forth the benefits of student learning from EDIS instruction, the report also states that there is little research to support these claims (p. 51). Similarly, the National Association for Research in Science Teaching (NARST) position statement on the NGSS says "the implementation of NGSS needs to be supported through quality research" (NARST, 2014, p.7). As such, there is a need for studies to provide evidence for the impact of EDIS instruction in science classrooms. Additionally, science education researchers are calling for studies to examine potential reasons behind changes in student learning when exposed to engineering design integrated science (Crotty et al., 2017; Mehalik, Doppelt, & Shun, 2008; Wendell & Rogers, 2013). The current study was conducted in response to a call from the science education research community to examine the extent to which science and engineering design integrated instruction impacts student learning outcomes in science and engineering, as well as the potential reasons for learning outcomes (NARST, 2014; NRC, 2009).

This study is significant because of its potential impact on three areas of study in science education - research on integrating engineering design into science classrooms, science teacher education programs, and the teaching and learning of engineering design in science classrooms. First, the current study addresses the following three gaps in the "science and engineering design integration in K-12 classrooms" literature: (1) the impacts of EDIS instruction on student learning outcomes in both science and engineering design, (2) teacher level factors that impact student learning outcomes, and (3) studies that involve pre-service teachers. Results from this study will add to what science education researchers currently know about integrating engineering design into science classrooms.

The study's significance also lies in its potential contributions to science teacher preparation. For example, the findings from this study support the training of pre-service teachers in EDIS instruction. This study suggests that if pre-service teachers are trained in how to integrate engineering design and science, they are likely to successfully develop and implement EDIS units in their science classrooms. However, if pre-service teachers do not receive this training, then it is unlikely that they will able to enact these units in science classrooms. Previous research suggests that there are very few pre-service science teacher education programs that explicitly address engineering and engineering design (Fantz, De Miranda, & Siller, 2011). Moreover, approximately 1% of elementary school, 7% of middle school and 14% of in-service high school teachers reported having college coursework in engineering (Banilower, Smith, Weiss, Malzahn, Campbell, & Weis, 2013). If teachers do not receive exposure to engineering in either their college courses or their teacher education program, it is unlikely that they will be prepared to teach engineering design integrated science. Results from this study can provide insight into how to train and support pre-service teachers as they plan for and enact engineering design integrated science instruction in their classrooms.

Lastly, the results of this study have practical significance for the teaching and learning of engineering design integrated science instruction in high schools. Previous research studies have found mixed results when measuring student learning across both science and engineering design. Results from this study can add clarity to the impact of EDIS instruction on student learning outcomes. Additionally, there is very little guidance for science teachers as to how they plan for and enact EDIS units in their science classrooms. Results from this study can provide teachers and teacher educators with an understanding of the teacher level factors that impact student learning in EDIS contexts. This would make the theoretical concept of integrating engineering design into science classrooms more practical for teachers. It would enable teachers to better implement EDIS lessons in their classroom and in turn, improve student learning outcomes.

Theoretical Framework

This study focuses on the impact of engineering design integrated science instruction on student learning outcomes in both science and engineering. Furthermore, the study attempts to identify teacher level factors that impact student learning outcomes in EDIS instruction. The intervention and interpretation of the results in the study were guided by the *Opportunity to Learn* (OTL) theoretical framework (Kurz, 2011).

Broadly speaking, the OTL theoretical framework says that student learning is impacted by the opportunities that they are provided to learn the curriculum. OTL is a framework that may explain the success (or lack thereof) of classroom instruction (Anderson, 1985). Researchers have attempted to quantify elements of instruction in order to critically analyze the instruction that students are provided. For example, in 2011, Kurz incorporated aspects of Carroll's (1963) focus on instructional time, Husén's (1967) emphasis of content alignment, and relevant literature to create a conceptual model of the opportunity to learn (see Figure 1). Kurz described OTL as,

> "a matter of degree related to the temporal, curricular, and qualitative aspects of a teacher's instruction. In OTL framework, a teacher must dedicate instructional time to covering the content prescribed by the intended curriculum using pedagogical approaches that address a range of cognitive process, instructional practices, and grouping formats." (Kurz, Elliott, Kettler, & Yel, 2014, p.162)

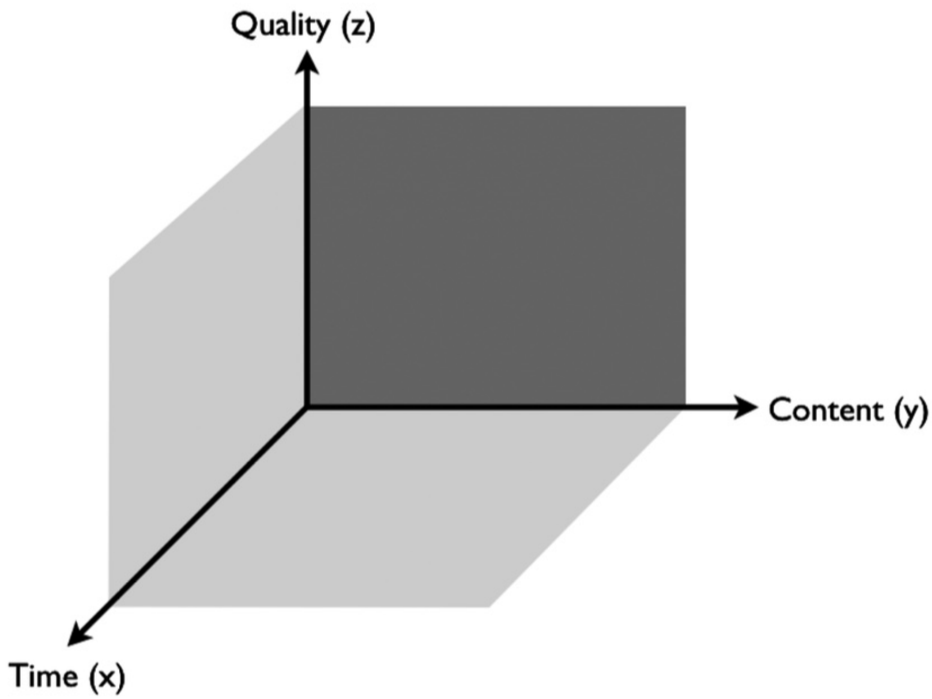

Figure 1. Conceptual Model of Opportunity to Learn (Kurz, 2011)

According to Kurz's (2011) model, the three dimensions of the OTL conceptual model can be further described by the following five indices: (1) instructional time, (2) content coverage, (3) cognitive processes, (4) instructional practices, and (5) grouping formats. The last three indices fall under the "quality" dimension. For the purposes of this study, Kurz's (2011) three original dimensions were used to represent the Opportunity to Learn.

Content Coverage

In the OTL framework, content coverage is the degree to which the content presented to the students is aligned with student achievement tests (Husén, 1967). In the current study, the pre-service teachers used the NGSS and VA SOLs to guide their content selection for EDIS units. Learning objectives based on the NGSS and VA SOLs were then used to create questions for the Science Content Knowledge (SCK) test. Questions for the Student Understanding of Engineering Design Process (SUEDP) test were developed using the NGSS as a guide. Therefore, there was a close alignment between what the students learned and what they were tested on. When looking at the degree of integration between the two content areas - science and engineering design - the students were equally assessed on both content areas. However, the degree to which the pre-service teachers incorporated both content areas varied across classrooms. Therefore, the degree of integration of both science and engineering design was assessed as a measure of content coverage.

Quality

According to the OTL theory, the more that students are exposed to evidence based high quality instructional practices, the greater the student learning outcomes. All pre-service teachers were trained in EDIS instruction during their science methods course in the spring 2017 school semester. Pre-service teachers received training by engineering experts and engineering education experts on instructional practices for EDIS units. All EDIS unit plans had some similar components (e.g. same EDP diagram) to ensure a minimum standard of quality. Beyond the common elements, the unit plans varied in terms of their overall instructional quality. Therefore, in order to determine the quality of each unit, they were assessed using the Curriculum Quality Rubric (Guzey, Moore, & Harwell, 2016a).

Instructional Time

With regards to instructional time, in the current study, our pre-service teachers carved out time in the curriculum to implement their EDIS units. Many of our pre-service teachers taught in classrooms with mentor teachers, who did not previously teach engineering design. By implementing EDIS units in their classrooms, pre-service teachers provided students with the time to learn the engineering design process and to create engineering design solutions using science concepts.

Summary of OTL & Study Alignment

Table 1 provides a summary of the connections between the OTL framework and the current study. As in several studies involving the OTL framework, this study used various types of statistical modeling to relate the teacher level factors to student learning outcomes (Kurz, 2011).

Table 1. OTL Framework and Study Alignment (Kurz, 2011)

Curriculum Dimension	Definition	Connection to Study
Content Coverage	Content coverage of the general curriculum standards and, if applicable, any custom objectives	Pre-service teachers aligned their instruction with the NGSS and VA SOLs. They also created the Science Content Knowledge (SCK) test question based on learning objectives and had engineering design assessments. The degree to which pre-service teachers integrated engineering and science varied across classrooms and was measured using *The Continuum Model for Engineering Design and Science Integration*" (Mumba, Chabalengula, Pottmeyer, & Rutt, 2017)
Quality	Refers to the quality of instruction. Many variables to measure instructional quality have been proposed. Some include examining the instructional resources and instructional practices occurring during a lesson.	Pre-service teachers were trained in instructional practices for teaching EDIS units and had several common instructional elements to ensure a degree of consistency. Unit plan quality was evaluated using the Curriculum Quality Rubric (Guzey et al., 2016a)
Time	Instructional time dedicated to teaching the general curriculum standards and, if applicable, any custom objectives.	Pre-service teachers allotted class time for students to learn about the engineering design process and to use the engineering design process and science concepts to develop a solution to a design challenge.

Definitions of Key Words & Terms

The following are definitions of key words as they are intended to be interpreted for the purposes of this research study.

Discipline - a specific area of study (i.e. science, engineering, math)

Design Challenge – an engineering focused problem that is open-ended

Engineering - any engagement in a systematic practice of design to achieve solutions to particular human problems (NRC, 2012, p.11)

Engineering Design - an iterative cycle of design that offers the greatest potential for applying science knowledge in the classroom and engaging in engineering practices (NRC, 2012, p.201-202).

Engineering Design Integrated Science - concept of teaching science content and practices through the use of the engineering design process

Engineering Design Process – a cyclical process used to solve an engineering design challenge.

Inter-Discipline Outcome Study – science and engineering design integrated intervention studies, which measure student outcomes in both science and engineering design

Next Generation Science Standards– national science standards that outline what a student should know and be able to do by the end of twelfth grade.

Prototype – a physical or digital replica of a design solution, which can undergo testing to determine the strengths and weaknesses of the design. It is similar to a model.

Science and Engineering Practices – mirror the practices of professional scientists and engineers" (NGSS Lead States, 2013, p. xx).

Science Content Knowledge Test – A test that each pre-service teacher created specific to the science learning objectives in their science and engineering design integrated lesson. Each test contained 4-5 open-ended questions.

Sequential Explanatory Mixed Methods Design - a type of design in which analysis of one of the strands (quantitative) precedes the analysis of the other (qualitative) (Creswell & Clark, 2011).

Single-Discipline Outcome Study - science and engineering design integrated intervention studies, which only measure student outcomes in either science or engineering design.

Student Learning Outcomes – measures that assess student learning (e.g. knowledge of cellular respiration) or student affective outcomes (e.g. perception of engineering design)

Teacher Factors – in this study, teacher factors refers to the broad category of elements that occur at the teacher or classroom level that all students, in a classroom with a particular teacher, would have the same exposure to.

Virginia Standards of Learning – "the commonwealth's expectations for student learning and achievement in grades K-12" http://www.doe.virginia.gov/testing/sol

Abbreviations

ED – Engineering Design

EDIS – Engineering Design Integrated Science

EDP – Engineering Design Process

ETK – Engineering Teaching Kits

IDO – Inter-Discipline Outcome

NGSS – Next Generation Science Standards

OTL – Opportunity to Learn

PD – Professional Development

PED – Perceptions of Engineering Design

SDO – Single-Discipline Outcome

SCK – Science Content Knowledge

SEP – Science and Engineering Practices

STEM – Science, Technology, Engineering, and Math

SUEDP – Students' Understanding Engineering Design Process

VA SOLs – Virginia Standards of Learning

CHAPTER 2: REVIEW OF THE LITERATURE

The purpose of this chapter is to review the literature on the integration of engineering design in K-12 science classrooms. This literature review addresses two lines of research on science and engineering integration in K-12 classrooms: (1) the impact on student learning outcomes, and (2) teacher level factors influencing student learning outcomes in science and engineering integrated instruction. The chapter ends with a summary of the emerging themes from the literature.

It is important to outline the scope of the current study. Studies reviewed in this chapter occurred in K-12 classrooms within the United States, with a majority of the studies focusing on middle and high school classrooms. While a few studies took place in engineering classrooms (Berland, Steingut, & Ko, 2014; Berland & Steingut, 2016), the primary focus of these studies was on integrating the science content. While there is promising engineering and science education research occurring in after school programs (Blanchard et al., 2015) and summer camps (Hammack, Ivey, Utley, & High, 2015; Hirsch, Berliner-Heyman, & Cusack, 2017), they are beyond the scope of this literature review, as this study was conducted in formal school science classrooms.

There are many studies which address student learning outcomes in science, technology, engineering and math (STEM) integration (Dare, Ellis, & Roehrig, 2018; Fan & Yu, 2017). However, this study focuses exclusively on engineering design and science as prescribed in the NGSS. As such, the studies in the literature review are specific to engineering design and science integration. Due to the nascent state of the research on engineering design integrated science instruction, there are a limited number of studies to review.

Science and Engineering Design Integration and Student Outcomes

In this study, the term "student learning outcomes" refers to both content outcomes (e.g. students' science content knowledge) and affective outcomes (e.g. students' perceptions of engineering design). Within the current literature on student learning outcomes in science and engineering design integrated interventions, studies fall into two categories based on their measured outcomes: Single-Discipline Outcome (SDO) studies and Inter-Discipline Outcome (IDO) studies. In this paper, SDO studies are on science and engineering design integration, but they assess student learning outcomes exclusively in either science or engineering design. IDO studies also address science and engineering design integration, but they assess student outcomes in both science and engineering design. For example, these studies measure students' science content knowledge and engineering career interest. Table 2 provides examples of both categories of studies – SDO and IDO.

Table 2. Examples of Single-Discipline and Inter-Discipline Learning Outcome Studies

Type of Science and Engineering Design Integrated Studies	Student Outcomes – both content and affective outcomes
Single-Discipline Outcome (SDO) Studies	
Marulcu and Barnett (2013)	Student understanding of simple machines *(science)*
Mehalik, Doppelt, and Schunn (2008)	Knowledge of core science concepts *(science)*
Silk, Schunn and Strand Cary (2009)	Scientific reasoning *(science)*
Wendell and Rogers (2013)	Science content and science attitudes *(science)*
Capobianco, Ji, and French (2015)	Engineering identity *(engineering)*
Inter-Discipline Outcome (IDO) Studies	
Apedoe et al. (2008)	Knowledge of chemistry Interest in engineering careers *(science and engineering)*
Guzey et al. (2016b)	Understanding of engineering design and practices, ecosystems, and data analysis Attitudes towards STEM *(science, engineering, and math)*

Studies on Single-Discipline Learning Outcomes

While SDO studies focus on science and engineering design integration, they assess student learning outcomes only in either science or engineering design, but not in both areas. Many SDO studies measure students' learning of only science content (Marulcu & Barnett, 2013; Mehalik et al., 2008; Schittka & Bell, 2011; Silk, Schunn & Strand Cary, 2009; and Wendell & Rogers, 2013). The focus on science content is important, because the integrated curriculum often occurs within the context of a science classroom. Furthermore, in an era of high-stakes testing, it is more likely that teachers will dedicate instructional time to integrating engineering design, if the lessons also improved students' science content knowledge.

Marulcu and Barnett's (2013) study provides an example of a SDO study in which students are assessed only in science, and not in engineering design. These researchers developed a design-based elementary science unit in which engineering design was used as the framework for teaching fifth graders about simple machines. A team of individuals, including a mechanical engineer, an aerospace engineer, an electrical engineer, and an engineering educator, created the lessons. In this eleven-lesson unit, students received the design challenge, learned about various simple machines, tested materials, built complex machines, modified their designs, and shared their findings. Each of the eleven lessons had specific objectives tied to state and national science standards. Results of the study indicated that the students' understanding of simple machines increased significantly after the integrated unit.

A strength of this study was the tight alignment between the lesson objectives, engineering practices, and the state standards, aided by the input of science educators and multiple engineers. Despite the numerous engineers involved in the project and the engineering design focus, students' engineering design understanding was not measured. This demonstrates a misalignment between the inter-disciplined learning objectives and single-discipline assessment. Ideally, measures of student learning would align with the learning objectives. Thus, if the learning objectives of a lesson include increasing science and engineering design knowledge, then students should be able to demonstrate gains in both of these areas. Without providing assessments in both disciplines, it is impossible to know whether these learning objectives were met. Additionally, Marulcu and Barnett (2013) do not provide insight as to why these learning gains were evident. They provide a description of the implementation of the unit, along with the successes and challenges in enacting the unit, but fall short of including hypotheses as to what specifically in the engineering design unit contributed to an increase in students' understanding of simple machines. In fact, they allude to this gap in their recommendations – suggesting that future research examine the difference between inquiry-based curriculum and design-based curriculum. Such studies would enable researchers to target specific elements of the engineering design units as catalysts for student learning.

Very few single-discipline outcome studies focused on engineering outcomes, such as engineering design knowledge (Crotty et al., 2017) and engineering identity (Capobianco, Ji, & French, 2015). In these studies, students significantly improved on the measured outcomes, after exposure to the integrated curriculum. For example, Capobianco et al. (2015) studied elementary students' engineering identity before and after they participated in a multi-week engineering design-based science unit adapted from the Engineering is Elementary curriculum. Third graders were presented with the following design challenge: "*Can you create a pair of Lego dancing birds that can rotate and sing? Use and apply knowledge of structures and forces, levers, wheels, axels, gears, and pulleys*" (p.279). Results from the Engineering Identity Development Scale indicated that students, who were exposed to the engineering design lessons, had a significantly better understanding of engineering as a career, than their peers in the comparison group. This study's research design suffered from a similar weakness as described in the Marulcu and Barnett (2013) study – the misalignment of the lesson objectives and the assessments. In describing the classroom intervention, Capobianco et al. (2015) stated that "Each unit included daily lesson objectives, corresponding science state standards, related assessments, and a multiday, grade-level engineering design task" (p. 278). Despite the inter-disciplinary nature of the lesson objectives and intervention, students were assessed in only a single discipline, engineering. Results from SDO studies (Capobianco et al., 2015; Crotty et al., 2017) focused on engineering outcomes suggest that formal exposure to engineering practices through integrating engineering design into science classrooms can have a positive impact on multiple engineering student outcomes.

Some SDO studies have examined the effectiveness of science and engineering design integrated instruction, as compared to other instructional models (Mehalik et al., 2008; Schittka & Bell, 2011; Silk et al., 2009; and Wendell & Rogers, 2013). Both Mehalki et al. (2008) and Silk et al. (2009) found that the integrated model of science and engineering design was more effective in improving students' learning of science content as compared to other instructional methods, such as inquiry instruction or textbook learning.

Results from Silk et al. (2009) are particularly striking. In this study, eight grade students, in a high-needs setting with a large percentage of economically disadvantaged students, engaged in an engineering design activity, in which they were tasked with designing an electrical alarm system to meet a need of their choosing. A pre-post comparison of student test scores showed that students improved their science reasoning skills over the course of the engineering design activity. Furthermore, the largest student gains were detected in the students who scored the lowest on the pre-assessment. As a whole, the students in the design group showed larger learning gains than their peers in the comparison groups – inquiry learning and textbook learning. These results are even more encouraging given that the engineering design group spent less time on the material, as compared to the textbook group.

The use of a comparison group is a strength to these studies, because it enables the researchers to show that the positive student outcomes are a result of the science and engineering design integrated instructional approach, and not merely the exposure to the science content. Findings from these studies suggest that when solely measuring science knowledge, the integrated teaching approach increases student learning.

Collectively, whether the measured outcomes are in science or engineering design, SDO studies support the use of a science and engineering design integrated curriculum for increasing student outcomes, even when compared to other instructional models.

Studies on Inter-Discipline Learning Outcomes

Positive findings. In inter-discipline learning outcome studies, Apedoe et al. (2008), Selcen Guzey et al. (2016), and Chiu and Linn (2011) reported positive impacts across all measured learning outcomes. Apedoe et al. (2008) investigated the impact of an engineering design unit on high school chemistry students' knowledge of chemistry concepts and their interest in engineering careers. Throughout the eight-week unit, students addressed the design challenge of creating a heating or cooling unit that runs on chemical energy. A strength of this study is the intentional identification of both the design and science goals within the engineering design process steps: create design, evaluate outcome, generate reasons, test ideas, analyze results, generalize results, and connect to big ideas (Apedoe et al., 2008, p.458-460). While many studies rely on a specific model of the engineering design process, they often lack clear identification of how both the engineering design and science components are related within the overall process. After the unit, students demonstrated more significant learning gains in chemistry content knowledge and interest in engineering careers than a comparison group. Thus, the engineering design integrated chemistry unit improved student outcomes in both science and engineering disciplines.

Similar results were found in the study conducted by Chiu and Linn (2011). This study examined two curriculum units which both used the Web-based Inquiry Science

Environment (WISE) technology platform to incorporate engineering into science classrooms. In one of the instructional units, *Airbags: Too Fast, Too Furious,* students applied their understanding of physics concepts to act as engineers engaged in airbag testing. In the *Chemical Reactions* unit, students explored chemistry concepts such as combustion reactions and limiting reactants to construct a potential solution to reduce global warming. Through the use of WISE, students were able to use visualizations and simulations to aid in their understanding of both the science and engineering concepts. Overall, students in both units demonstrated learning gains across both the science and engineering concepts.

Negative findings. In the IDO study conducted by Tran and Nathan (2010), high school students exposed to the engineering integrated math and science curriculum, *Project Lead the Way*, had smaller achievement gains on both state math and science exams than students who were not exposed to this curriculum. This finding is particularly problematic for engineering design integration because the curriculum, *Project Lead the Way*, was a featured model of STEM integration in the NRC's 2009 report. Researchers considered multiple explanations for this finding, such as a misalignment between the achievement tests and the curriculum. However, they were unable to reach any conclusions because all of the data collected was quantitative archival data. Although the findings of this IDO study do not support the use of integrating engineering design and science as a way to increase student learning, the researchers cannot provide a concrete explanation for their findings. Including qualitative data sources such as interviews or classroom observations may provide a greater understanding of why this particular curriculum does not result in student learning gains.

Mixed findings. Additional IDO studies have mixed findings, in which the integrated curriculum only produces learning gains in certain contexts (e.g. Berland et al., 2014; Glancy, Moore, Guzey, & Smith, 2017; Guzey et al., 2016b). For example, Guzey et al. (2016b) conducted a study in which middle school students developed a nesting platform for the state bird. Pre and post-content tests were used to measure student understanding of science, math, and engineering concepts. The only statistically significant finding for student achievement occurred for life science students in special education. The strength of this study was the use of student demographic data to determine whether or not student learning outcomes were the same for all groups of students. While the achievement results of this study largely do not support the use of the integrated curriculum, findings from pre and post attitudinal surveys show that engaging in the lesson significantly improved students' attitudes towards science, math, and engineering.

These mixed findings can result in various recommendations for integrating ED into science classrooms. Results from the Guzey et al. (2016b) study, in which middle school students developed nesting platforms, suggest that for this lesson, the only students who demonstrated statistically significant gains in learning were students with disabilities and their gains were only significant on the science measure and not the engineering or math assessments. However, all students did receive the benefit of an increased interest in engineering careers. Increasing interest in engineering careers is a worthy cause. However, the lack of positive findings for science achievement amongst all students may cause teachers to avoid implementing the fifteen 50-minute lessons, especially if students are expected to pass high-stakes tests. It is evident from this review, that collectively, the results from IDO studies do not provide a consistent picture of the effectiveness of science and engineering design integrated instruction.

Students' Abilities to Make Connections

Another studied student outcome is the extent to which students are able to make connections across disciplines during science and engineering design instruction. For example, Crismond (2001) compared "non-expert" designers to "expert" designers, while they completed a science focused investigate-and-redesign task. Through the use of video-analysis of the lessons, Crismond (2001) found that the "non-expert" designers missed opportunities to use science when analyzing their design ideas. The lack of students' abilities to make connections across the science and engineering disciplines is the crux of the research by Chao et al. (2017) "*Bridging the Design-Science Gap with Tools: Science Learning and Design Behaviors in a Simulated Environment for Engineering Design*". Findings from their research suggest that design tools as well as specific design actions, such as representation, analysis, and reflection, can improve science learning, and thus bridge the gap between design and science.

Berland et al. (2014) conducted a study to examine how high school students interact with engineering design lessons and how they make connections to science and math. One of the strengths of the study was the use of both quantitative and qualitative research methods. Researchers administered a survey to assess students' understanding of the engineering design process. After completing the survey, researchers conducted student interviews to further explain their survey results. Berland et al. (2014) found that students favored and valued components of the engineering design process that are more qualitative and engineering focused, such as identifying the user needs, brainstorming multiple solutions, iterative testing, and refining a design solution. Researchers found that students did not mention or value aspects of the engineering design process that may be viewed as more quantitative and are important for making connections to science and math. The researchers categorize the following as quantitative components of the engineering design process: exploration of key math and science principles, quantification of the qualitative needs and goals, a systematic process for choosing between solutions, and mathematical modeling (Berland et al., 2014).

The combination of the mixed results in the IDO studies and the findings that students often fail to make (or fail to value) connections between disciplines (Berland et al., 2014; Chao et al., 2017; Crismond, 2001) suggests that improved outcomes in one discipline do not guarantee improved outcomes in another discipline. If students are unable to see the connections between content areas, then it is unlikely that they will be able to reap the full benefits of a science and engineering design integrated lesson and in turn perform well in both science and engineering. It is crucial that during their instructional planning and implementation, teachers are thoughtful and explicit about how they integrate engineering design and science because students on their own, may not be able to make these inter-disciplinary connections.

Factors that Influence Student Learning Outcomes

Elements of Engineering Design

While the previously mentioned SDO and IDO studies measured student learning outcomes in the presence of an engineering design integrated science unit, many of them (e.g. Apedoe et al., 2008; Capobianco et al., 2015; Marulcu & Barnett, 2103) fell short of providing explanations for the learning gains that occurred. While this may be considered beyond the scope of the studies focused on measuring learning gains, the nascent state of EDIS research would greatly benefit from researchers at least providing detailed explanations of what occurred during the implementation and providing hypotheses as to why they think this learning occurred. To exclude this information is a missed opportunity for experts to provide their professional insight into the mechanisms that are essential for student learning in EDIS contexts.

Several of the studies did provide potential explanations for student learning outcomes. For example, in Mehalik et al. (2008) researchers first demonstrated a greater learning of science concepts for students engaged in the engineering design activity, as compared to their peers in a scripted inquiry approach. Additionally, it should be noted that the students who benefited the most from the engineering design instruction were low-performing minority students. The overall difference in science learning, between students in the engineering design group and those in the scripted inquiry group, necessitated that the researchers provide potential explanations. They posit that the difference in learning gains may be mediated by allowing students to ask their own questions and to design their own experiments to test their own ideas (p.81). Thus, according to Mehalik et al. (2008) student choice and flexibility to pursue student ideas may be a crucial element in the success of engineering design integrated units.

Similarly, Guzey et al. (2016b) provided potential explanations for the student learning gains found in their study. As previously mentioned, in their study middle school students developed nesting platforms through engineering design. Results indicated that students had an increased interest in engineering careers and the only statistically significant gain in science achievement was for the special education students. While Guzey et al. (2016b) did not make any definitive connections, they suggested that increased student motivation and interest may in part be influenced by the intellectual creativity that the activity afforded the students. Additionally, they suggest that the multiple-solution, open-ended nature of the engineering design activity may have motivated the special education students to participate and thus learn from the activity.

In another study conducted by Selcen Guzey et al. (2016), the researchers focused specifically on both student interest in science and engineering as well as particular instructional strategies that may impact student interest. Researchers provided the following three strategies as explanations for increased student interest in science and engineering following the activity: (1) Using engaging and motivating context, criteria, and constraints; (2) having students apply science to solve engineering challenges; and (3) promoting autonomy during engineering design instruction (p.418).

Many of the studies measuring student learning outcomes from EDIS instruction in science contexts neglect to provide hypotheses as to why the learning may be occurring. Many researchers are aware of this absence and call for future studies to examine the mechanisms that may help to explain student learning (Crotty et al., 2017; Mehalik et al., 2008; Wendell & Rogers, 2013). Several studies do include this information. A common theme emerging from this literature is the importance of student autonomy during the design process.

While I would be remiss to not acknowledge the research occurring in the field of design-based learning, the purpose of this study is to examine engineering design infused into science classrooms and the learning outcomes on students. Thus, based on the context of the study, this literature review does not contain studies focused purely on design-learning. However, one seminal study should be noted. In their approach to used design to facilitated learning, *Learning by Design,* Kolodner (2002) provide five overarching strategies for learning through design – (1) foregrounding the learning of skills and practices through iterative cycles; (2) frequent individual and public practice of skills; (3) establishing need; (4) making recognition of applicability automatic; and (5) establishing and enforcing expectations through building and sustaining the culture (p.10-11).

It is understandable that researchers may feel that this information extends beyond the scope of their study. However, without including at the very least a description of the implementation of the EDIS intervention along with identifying hypothesized explanations for the gains in student achievement, it will be difficult to replicate these results in other contexts.

Science and Engineering Design Integration Models

In order to discuss how the disciplines are integrated, there is a need for a common framework to categorize types of integration. One integration model focuses on the extent to which engineering design and science concepts are presented and integrated within a lesson (Mumba, Chabalengula, Pottmeyer, & Rutt, 2017). This model is a continuum, in which maximum integration occurs at the center of the continuum, and either end of the continuum represents no integration, either completely engineering design or entirely science. The continuum consists of the following five variations: (1) Independent Engineering Design Activity; (2) Engineering Design Focus Activity; (3) Balanced

Engineering Design & Science Activity; (4) Science Focus; and (5) Independent Science Activity. Lessons and activities are categorized based on their engineering design and science core ideas, learning objectives, and assessments. By using this model, science teachers can identify the degree of integration within their lesson, which can result in an appropriate alignment between learning objectives, student learning outcomes, and teacher expectations.

Guzey et al. (2017b) also describes a continuum model. This model addresses the timing of the engineering design integration into the lesson/unit. Guzey et al. (2017b) proposes the following three broad categories of integration: *add-on, explicit,* and *implicit*. *Add-on integration* is defined as a curriculum that is largely science focused with an engineering design project occurring at the end of the unit. *Explicit integration* occurs when science concepts are actually taught through engineering design. In this model, students are actively learning the science content while engaged in the engineering design process. *Implicit integration* lies between *add-on* and *explicit* and is "engineering that is embedded throughout a science unit, but the teacher may supplement less structured occasions for learning engineering prior to the engineering challenge that takes place at the end of the unit." (p. 4).

In addition to creating models for identifying types of integration, there is a need to determine the impact that these types of integration have on student learning. While *add-on integration* is the most common, there is a concern that without clear integration of the science content into the engineering design process, these projects will become arts and crafts projects (Guzey, Tank, Wang, Roehrig, & Moore, 2014). Furthermore, research shows that students gravitate towards the more qualitative design aspects of a science and engineering design integrated lesson, instead of focusing on applying the science (Glancy et al., 2017). Thus, if the teacher does not explicitly integrate the science content into the engineering design process, then students are unlikely to make the connections on their own.

In a study of middle school students, Guzey et al. (2017a) used multi-level modeling to determine that students who engaged in an EDIS curriculum with the *explicit integration* approach performed better on engineering post-assessments than their peers learning under *implicit* or *add-on integration*. Guzey et al. (2017a) argue that "simply adding engineering into science instruction is not necessarily supportive of better student learning—teaching high-quality curriculum units that purposefully and meaningfully connect science concepts and the practices of those of engineering is essential to produce positive student outcomes" (p.219). Similarly, Crotty et al. (2017) found that students exhibit greater learning gains when the engineering design concepts are *explicitly integrated*. By providing clear connections between the disciplines and ensuring that learning objectives contain both science and engineering practices, students may exhibit greater achievement gains across disciplines. However, if the curriculum is heavily focused on one discipline and not explicitly integrated, it is unlikely that students will perform well on measures across multiple disciplines. Research has indicated that best practices for science and engineering design integrated teaching include a curriculum that is explicitly integrated. Despite research that suggests how the material is integrated can impact student learning (Crotty et al., 2017; Guzey et al., 2017a), many current studies do not report how the content in their study is integrated.

Identifying the type of integration in a lesson/unit is important for both science teachers and science education researchers. For science teachers, they need to be able to understand the components of an explicit integration lesson, so that they can ensure that their instruction contains explicit integration. Additionally, science teachers need to be able to align assessments with the integrated curriculum. For example, if a lesson uses an add-on integration approach (Guzey, Ring-Whalen, Harwell, & Peralta, 2017b), then teachers should recognize that students might not show achievement gains in science content knowledge.

Science and Engineering Design Lesson Implementation

In this literature review, implementation refers to how the teacher enacts the intended lesson/unit plans and how students and teachers interact throughout the lesson. Several researchers have examined how teachers implement their engineering design integrated science lessons and the impacts on student learning. (Berland & Steingut, 2016; Guzey et al., 2017b; Schnittka, 2012).

Schnittka (2012) examined the impact of a middle school teachers' implementation of a science and engineering design integrated unit on student learning of science concepts across two different class periods. One of the class periods was identified as the advanced-level class and the other was the standard-level class with many students with learning disabilities. The researcher found that both the teachers' expectations of the students and her implementation of the lesson varied widely between both classes (Schnittka, 2012). In the standard-level class, there were fewer opportunities to learn science content through demonstrations and more non-instructional time. Additionally, the students in the lower track did not learn the scientific content as well as the higher track students. While, other factors may contribute to the differences in learning, Schnittka (2012) suggests that the varied implementation of the lesson may have played a role.

Additional research has examined the relationship between implementation and student learning. For example, Berland and Steingut (2016) found that "teachers' pedagogical approach and the classroom culture have a large effect on the degree to which students connect their design work to their desired concepts" (p.30). Because student learning in science and engineering design integrated lessons is often impeded by students' lack of ability to connect content (Berland et al., 2014), changes in teacher implementation may result in gains in student learning.

There is some overlap between teacher implementation and content integration, because teachers may favor instructional strategies that privilege certain content. For example, if a teacher chooses to teach using small groups and allots the majority of the class time to prototype building, then students might not receive as much science content. As a result, explicit integration may be absent. Research by Guzey et al. (2017b) demonstrates the interconnectedness of content integration and teacher implementation. This study followed one middle school teacher across three years. The researcher documented how the same science and engineering design lesson was implemented and its impact on student learning of engineering and science content. Results indicated that in each year the teacher used a different model of integration (add-on, implicit, and explicit) and varied how he discussed engineering and science practices with the students. Students demonstrated the most growth on science and engineering assessments during the third year, in which the teacher used an explicit integration approach, referred to students as engineers, and facilitated richer and more scaffolded discussions.

Despite the relationship between classroom implementation and student learning, many studies do not explain how teachers implemented the science and engineering design integrated lesson. Instead, studies focus on the in-service teacher professional development program and the impact of these integrated lessons on student learning. Results of these studies assume that teachers taught the lessons exactly how they were instructed to through their science and engineering design integrated professional development, despite research suggesting otherwise (Dare et al., 2014). For example, although teachers in professional development may learn the importance of assuming a facilitator role during integrated science and engineering design instruction (Cunningham & Carlsen, 2014), they may not use this strategy when they are in their own classrooms. Furthermore, not all teachers hold the same beliefs about STEM integration, which may lead to a variety of teaching and implementation practices (Wang, Moore, Roehrig, & Park, 2011).

Therefore, it is important to examine how teachers actually implement these integrated lessons in their classrooms. In assessing teacher implementation, researchers often rely on qualitative measures, such as classroom observations (Crotty et al., 2017; Wang et al., 2011), lesson plans (Capobianco & Rupp, 2014; Peterman, Daugherty, Custer, & Ross, 2017), teacher logs (Crotty et al., 2017), and teacher interviews (Wang et al., 2011).

There are several benefits to including teacher-level qualitative factors, such as content integration and teacher implementation, into science and engineering design integrated research. First, these measures have been shown to impact student learning (Schnittka, 2012). As such, they may help explain the mixed results from inter-discipline outcome studies. Second, qualitative factors include direct observations or views from participants, and thus, give participants an opportunity to provide their opinion. Teachers are given opportunity to explain their instructional decisions, practices, and changes they made in class, and students are given a chance to explain the responses they provided in quantitative protocols. Third, by including these measures researchers can provide teachers with best practices and strategies for translating the NGSS into practice.

Summary of Literature Review

Through the review of the literature on science and engineering design integrated instruction, six main themes emerge: (1) Results of single-discipline learning outcome studies indicate that science and engineering design integrated lessons positively impact student learning; (2) Inter-discipline outcome studies reported mixed results as to the impact of science and engineering design integrated lessons on student learning; (3) Many studies do not attempt to provide potential explanations for student learning outcomes; (4) Explicit integration of the two disciplines is an important factor for student learning in science and engineering design integrated lessons; (5) Teacher implementation is an important and understudied factor for student learning in science and engineering design integrated lessons; and (6) There is a lack of research on pre-service teachers in engineering design integrated science research.

The first two themes focus on the impact of integrating engineering design into K-12 science classrooms on student learning outcomes, such as, science content understanding, engineering design understanding, and changes in student attitudes. Despite the integrated nature of the lessons, many science and engineering design integrated studies assessed outcomes in only one discipline (either engineering or science). These studies overwhelmingly support the integration of engineering design into science classrooms (Mehalik et al., 2008; Wendell & Rogers, 2013), due to their positive results. However, when multiple outcomes were measured across both engineering and science disciplines, the results were mixed (Glancy et al., 2017). This is problematic because the NRC (2009) states that students should receive learning benefits across disciplines, when integrating engineering design into science classrooms.

The third, fourth, and fifth themes explore specific teacher level factors that impact student learning in science and engineering design integrated contexts (Berland & Steingut, 2016; Guzey et al., 2016b; Wang et al., 2011). Specific elements of the engineering design process that may contribute to student learning gains is an underreported component of many studies. Two important teacher level factors that do reoccur in the literature include: the type of integration between the two disciplines (Crotty et al., 2017; Guzey et al., 2017a), and the teacher implementation of the lesson (Dare et al., 2014). Content integration can be assessed several ways – the extent to which content is integrated across disciplines (Mumba et al., 2017) and the timing of the integration (Guzey et al., 2017a). Findings from these studies suggest that there is need to examine student learning in science and engineering design integrated instruction should include measures of content integration and classroom implementation.

Lastly, a common theme in studies in the review of the literature is that participants were in-service and not pre-service teachers. This was not a selection criterion, but a result of the scarcity of research on pre-service teachers and engineering design integrated science.

Directions from Literature Review

From this literature review, it is evident that there are three main issues in science and engineering design integrated studies that need to be addressed. First, there is a need to measure student learning outcomes in both science and engineering disciplines. Because these EDIS units have inter-discipline (both science and engineering design) learning objectives, it is essential to measure outcomes in both disciplines to ensure that the goals of the unit are being met.

Second, there is a need to incorporate qualitative methods within the research design. Many studies present only the results of quantitative student learning measures after students have been exposed to an intervention (Crotty et al., 2017; Mehalik et al., 2008; Wendell & Rogers; 2013). This research design does not provide an explanation as to what elements of the EDIS intervention lead to those results. Similarly, very few studies address the way in which the intervention was implemented and the way in which the content was integrated. The use of qualitative data (i.e. classroom observations and interviews) can further explain the quantitative results and may help to identify key factors that are important in effective science and engineering design integrated instruction.

Lastly, there is a need to expand the literature to include pre-service teachers and how they teach EDIS in schools. Currently, pre-service teachers are absent from the conversation on implementing integrated engineering design and science units during their student teaching placement in schools. However, as the integration of engineering design into science classrooms continues to gain momentum, pre-service teachers are likely to also teach engineering design integrated science after they are hired in schools.

As such, there is need for more research in the following three areas: (1) the impacts of EDIS instruction on student learning outcomes in both science and engineering design, (2) teacher level factors that impact student learning outcomes, and (3) studies that include pre-service teachers. In an effort to address these gaps in the literature, our science teacher education program instituted a 10-week intervention designed to teach pre-services about engineering, engineering design, and how to develop and teach engineering design integrated science units in schools. This sequential explanatory mixed methods study follows these pre-service teachers into their student teaching placements to examine the extent to which they plan for and implement their EDIS units and the impact that these units have on student learning outcomes in both science and engineering design.

CHAPTER 3: METHODS

The purpose of this chapter is to describe the methods for the research study. The chapter presents the research questions, research design, researcher as instrument statement, context and setting of the study, participants, and the engineering design integrated science interventions in teacher education and in schools. Next, the chapter describes data collection instruments, procedures, and analyses. The chapter ends with a summary of the data sources and analyses. The current study addressed the following research questions:

1. To what extent does engineering design integrated science instruction, situated in an OTL model, impact student learning outcomes in science (as measured by science content knowledge) and engineering design (as measured by understanding of engineering design and perceptions of engineering)? *(Quantitative)*
2. To what extent does the qualitative data (unit plan, classroom observations, student responses & teacher interview response) from an exemplar of EDIS instruction, within a high *Opportunity to Learn* environment, help to explain the quantitative results of student learning outcomes? *(Qualitative)*

Research Design

The study employed a sequential explanatory mixed methods design (see Figure 2), in which the quantitative data analysis preceded the qualitative data analysis (Creswell & Clark, 2011; Teddlie & Tashakkori, 2009). In explanatory mixed methods studies, the data analysis of one method (quantitative) occurs first, with the second method analysis (qualitative) following to help explain the quantitative results (Creswell & Clark, 2011).

The quantitative data was used to measure the impact of the science and engineering design integrated intervention on the following student learning outcomes: science content knowledge, engineering design knowledge, and perceptions of engineering design. As shown in Figure 2, these student learning outcomes were derived from pre-posttests and surveys. In this study, the students' perceptions of engineering design survey is the source of quantitative data, while the two student tests, Science Content Knowledge (SCK) and Student Understanding of Engineering Design Process (SUEDP) are qualitative data that were quantitized. Additionally, the pre-service teacher unit plans were also quantitized. The quantized data provided measures of the OTL framework for use in the data analysis procedures described below. The qualitative data collection (student responses, classroom observations, unit plans, and pre-service teacher interviews) occurred before, during, and after the EDIS intervention in science classrooms.

In the first phase of data analysis, descriptive analysis, dependent t-tests, a multi-level modeling analysis, and a multiple regression analysis were conducted using the quantitized qualitative data and the quantitative data to examine the impact of EDIS instruction on student learning outcomes. In these analyses, measures of the OTL framework were used to determine the impact of EDIS instruction on student learning outcomes. Based on these results, a classroom with high post-test scores on the student outcome measures and high ratings on the measures of the OTL framework was selected for the in-depth qualitative analysis. The rationale behind the selection was a desire to examine in-depth an exemplary case. In the second phase of the data analysis, classroom observations, the unit plan, a pre-service teacher interview, and student responses to reflection questions were used for the following two reasons: (1) to describe practically what occurred in a classroom scoring high on the OTL framework and with strong student learning gains and (2) to further explain the quantitative findings from phase 1 of the analysis.

As such, the quantitative and qualitative strands interacted at two critical points. First, the results of the quantitative phase informed the selection of the classroom to analyze in the qualitative phase. Second, during the interpretation of the results, the major quantitative findings for an EDIS unit with a high OTL environment were further explained using results from the qualitative analysis. This research design allowed for a greater understanding of the impact of EDIS instruction on student learning outcomes, as well as an understanding of what occurs during a well-developed EDIS in a high OTL environment and how the participants reflected on their EDIS experience and learning.

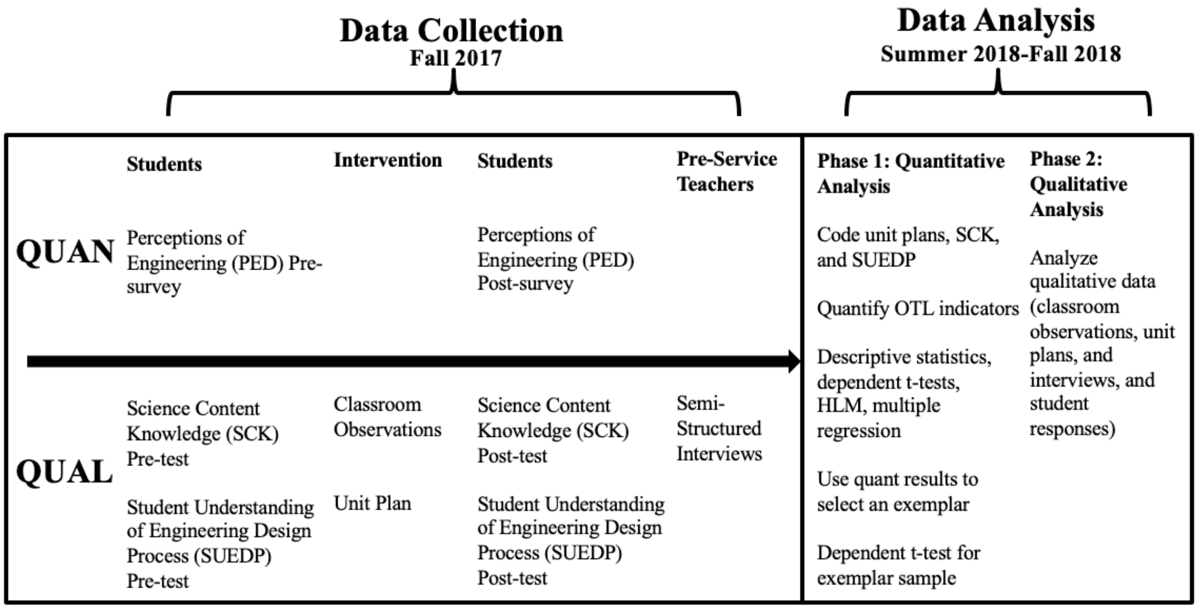

Figure 2. Sequential Explanatory Mixed Methods Research Design

Researcher as Instrument Statement

Despite the best attempts at complete objectivity, often research is influenced in some way by the researcher. Erickson states, “we always bring to experience frames of interpretation or schemata” (Erickson, 1986, p.140). Thus, in order to provide both transparency and context to my research, a researcher as instrument statement is critical and provided below.

I am currently a fourth-year doctoral student in science education in the department of curriculum, instruction, and special education at the University of Virginia. I have taken several graduate level courses in quantitative, qualitative, and mixed methods research. In the past three years, I have participated in externally funded research projects including: *University teaching assistants’ pedagogical content knowledge for chemical bonding*, *Representation of essential features of inquiry in practitioner journals,* and *Pre-service science teachers’ understanding of engineering practices.* Within these research projects I have assumed various roles and responsibilities including: data collection, data coding, quantitative and qualitative data analysis, writing manuscripts, and presenting findings at science education conferences. I have also engaged in writing research grants for internal funding. As part of my training, I have been involved in co-teaching science methods courses and field placement courses for pre-service science teachers. I have also served as a supervisor of pre-service science teachers during their student teaching. I have received training in teacher evaluation using the Classroom Assessment Scoring System (CLASS) (Hamre, Pianta, Mashburn, & Downer, 2007). CLASS is an observational framework, which focuses on classroom interactions between teachers and students. This experience has provided me with the necessary skills to observe pre-service science teacher instruction in this current research study.

Prior to becoming a doctoral student, I taught high school biology and earth science for two years in a high-needs public school. Through this experience, I gained teaching experience, became familiar with the high school science content and challenges students experience in learning science. I also developed a sound understanding of the daily life of a public-school teacher.

In this study, I served as a teaching assistant in science methods courses, in which the intervention was conducted. While this gives me a unique understanding of the research participants' coursework and their frames of reference, it may have caused some biases the way in which participant pre-service teachers interacted with me. Therefore, throughout the research process, I aimed to minimize biases by keeping a methodological journal and documenting potential sources of bias. Furthermore, another expert and I independently coded qualitative student learning data and the pre-service teacher unit plans, and inter-rater reliability was calculated.

Methodology

Context & Setting of the Study

This study was conducted within a larger National Science Foundation (NSF) funded Engineering Education project. The current study focuses on the project data that was collected in spring 2017 and fall 2017. In spring 2017, pre-service teachers learned about the engineering design process and how to integrate engineering design in science instruction. In the fall 2017 semester, the participants student taught in local public schools and implemented their engineering design integrated science units in their student teaching placements.

The secondary science teacher education program, in which participant pre-service teachers were enrolled, required them to complete two science methods courses, one in the fall and another one in the spring semester. In the fall 2016 semester, prior to the study, pre-service teachers 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. Pre-service teachers 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 spring 2017, pre-service teachers were enrolled in the second science methods course, where they learned about the project-based and problem-based teaching strategies, the NGSS, the engineering design process, how to develop engineering design integrated science unit plans, and best practices for teaching and assessing student learning in EDIS lessons. The instruction on engineering design integrated science teaching took place over the course of ten weeks. The learning objectives for engineering design integrated science teaching were to: (a) describe the three dimensions of the NGSS, (b) explain and apply the engineering design process, (c) develop and teach engineering design integrated science units plans, (d) demonstrate how to assess student learning in engineering design integrated science teaching, and (e) locate and describe teaching resources for engineering design integrated science teaching.

These objectives were addressed through the following lessons and activities. First, pre-service teachers learned how to read the three dimensions in NGSS – disciplinary core ideas, science and engineering practices, and cross-cutting concepts (NGSS Leads States, 2013). Second, pre-service teachers were asked to choose one of the lesson plans that they had previously created and adapt it to align with the appropriate NGSS core ideas and science and engineering practices. Next, pre-service teachers read articles from science practitioner journals to gain exposure to examples of how to integrate engineering design into science classrooms. Whole class discussion were held to analyze the different integration models found in the practitioner articles that pre-service teachers read. For the remaining 9 weeks of engineering design instruction, three guest instructors co-taught the course, along with the science education instructor. The guest instructors were two engineering professors from the college of engineering and one engineering education professor from within our science teacher education program. Instructors introduced engineering by comparing and contrasting it to science. Then, pre-service teachers learned about engineering, the principles of engineering, and the engineering design process. The engineering design process was compared to the scientific method, and pre-service teachers discussed the similarities and differences between the two models.

While there are numerous engineering design process models, the pre-service teachers were exposed to the Informed Engineering Design Model (See Figure 3) (Burghardt & Hacker, 2004; Chiu, Malcolm, Hecht, DeJaegher, Pan, Bradley, & Burghardt, 2013). As shown in figure 3, 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. A description of each design element is provided in the last column of Figure 3.

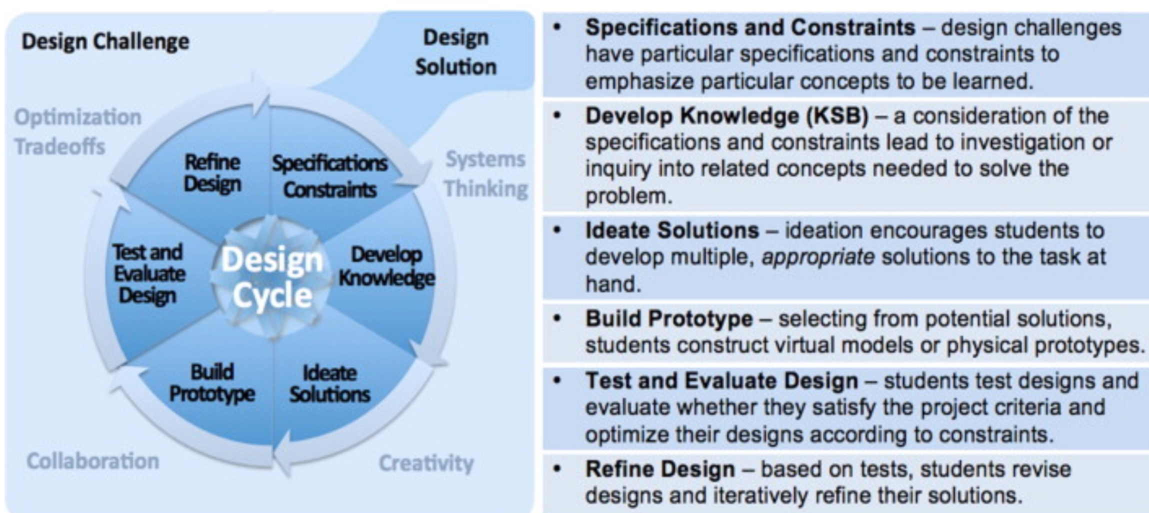

Figure 3. Informed Engineering Design Instructional Model (Chiu et al., 2013)

After formal introduction to engineering and engineering design, pre-service teachers engaged in hands-on engineering design activities and critically evaluated them from both the student and teacher perspective. Pre-service teachers engaged with the Engineering Teaching Kits (ETKs) (Richards, Hallock, & Schnittka, 2007), which were designed by one of the engineering professors, who co-taught the course. 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 energy, force, and friction to design a solar-powered car that can pull a load (Schnittka & Richards, 2016). After engaging with the ETKs, pre-service teachers discussed the successes and challenges of the activities from both student and teacher perspectives.

Next, pre-service teachers adopted the role of a classroom teacher as they learned about engineering design process knowledge, teaching strategies, and methods of assessing student learning in engineering design integrated science classrooms. Then, in order to demonstrate their instructional planning skills, pre-service teachers developed their own EDIS units. Pre-service teachers gathered resources, created teacher guide manuals, and developed engineering design integrated science units to be used in their student teaching classrooms during the fall 2017 semester.

While pre-service teachers were student teaching during the fall 2017 in middle and high schools, some were employed on a provisional teaching license and student taught in their own classrooms along with the support of a mentor teacher within the school. As part of the requirement for the Noyce Scholarship program, all pre-service teachers were required to implement an engineering design integrated science unit in their student teaching placements. While there were 16 pre-service teachers who enrolled in the spring 2017 methods course and student taught in fall 2017, only nine were used in the study. The study focused specifically on high school settings, and thus the pre-service teachers, who taught in middle schools were not included. Furthermore, pre-service teachers who did not collect all of the necessary assessment data from their students who received EDIS instruction, were also not included.

Participants

Participants included nine secondary science pre-service teachers, who enrolled in the secondary science education program at a Mid-Atlantic research university, as well as, the 460 high school students, who received EDIS instruction from these pre-service teachers (see Table 3). There were seven female and two male pre-service teachers. One pre-service teacher was in his fourth year of his undergraduate degree program, while eight of the participants already had Bachelor's degrees. The pre-service teachers either had or were pursuing degrees in biology, chemistry, and earth science. All pre-service teachers were enrolled in the science education program to obtain a Masters in teaching and a teaching license. None of the pre-service teachers had formal K-12 science teaching experience. Three pre-service teachers reported previously taking an engineering course.

Engineering Design Integrated Science Intervention in Schools

The engineering design integrated science intervention took place in high school science classrooms in the fall of 2017. Pre-service teachers created their own EDIS units in collaboration with their science methods instructor. While all of the units contained the same steps of the engineering design process (see Figure 4), the science topics and content varied across the units. Table 3 shows the list of the EDIS units that the pre-service teachers taught during their student teaching placements.

Table 3. Engineering Design Integrated Science Units Taught

Pre-Service Teacher*	Science Content Area	Number of Students**	Unit Length (min)	EDIS Unit Title and Description
Abigail	Chemistry	68	130	Cheetos Engineering *Students take on the role of engineers tasked with determining the number of kilocalories in a serving of Frito-Lay Cheetos.*
Beth	Anatomy and Physiology	54	360	Building Synthetic Tissues *Students pretend to be biomedical engineers employed to design a low-cost synthetic tissue for low-resource medical schools & labs.*
Marissa	Animal Studies	12	90	Saving the Bees *Students act as conservation engineers responsible for designing a bee hive to support a large colony, while meeting a set of constraints.*
Mark	Biology	15	315	Engineering Potatoes *Students take on the role of agricultural engineers employed with designing a liquid solution in which a potato can grow without gaining or losing water.*
Mary	Biology	107	315	Creating Cell Membranes *Students are biomedical engineers tasked with designing a functioning membrane for patients with cell membrane disorders, such as cystic fibrosis.*
Robert	Physics	33	270	Bottle Rockets *Students are engineers assigned to build a water rocket designed to meet specific criteria and constraints.*
Samantha	Earth Science	42	90	Cookie Mining *As engineers, students design the best process for mining resources given specific criteria and constraints.*
Tess	Earth Science	58	90	Cleaning Up Oil Spills *Students act as engineers from the Department of Environmental Quality and are tasked with designing a cost-effective method to clean up an oil spill.*
Theresa	Biology	71	360	Containing Slime Molds *Students are engineers responsible for designing a small-scale quarantine facility to contain the spread of a hypothetical disease represented by slime mold.*

**Note.* Names are pseudonyms
** Number of students with complete data only, does not include students removed for missing data, analysis used pairwise comparison so exact numbers may vary based on the outcome in question.

All high school students were exposed to the same introductory presentation on engineering design and completed the Student Understanding of Engineering Design Process (SUEDP) test and Perceptions of Engineering Design (PED) survey before and after EDIS instruction. Students also took the Science Content Knowledge (SCK) test that was aligned with the EDIS unit each teacher taught.

Students completed the pre-tests and pre-survey before any formal instruction on engineering design integrated science and the post-tests and post-survey after EDIS intervention (see Appendices A, B, and C). The pre-service teachers provided an interactive presentation to introduce students to engineering and the engineering design process. The engineering design process was presented to the students using the model depicted in Figure 4. This model contains the following design elements: identifying the need or the problem, conducting background research, brainstorming possible solutions, selecting the best solution, constructing the prototype, testing the prototype, presenting solutions, and redesigning.

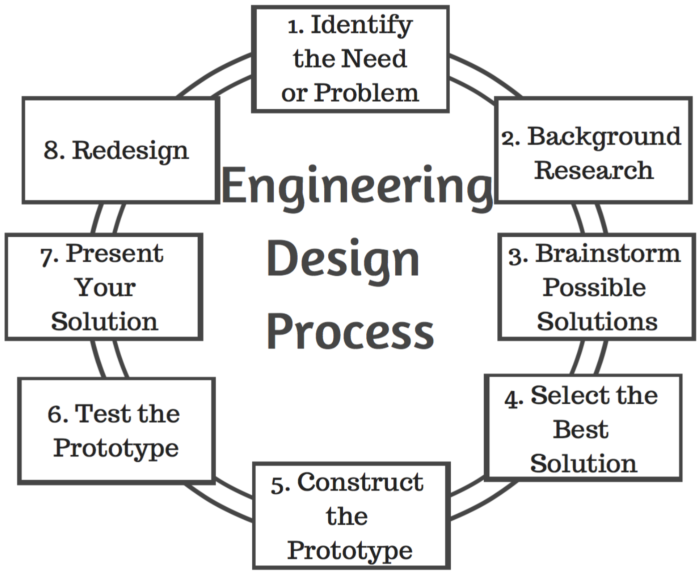

Figure 4. Engineering Design Process Model

Additionally, students learned about the similarities and differences between the engineering design process and the scientific method (see Table 4 below).

Table 4. Comparison of Engineering Design Process and the Scientific Method

Engineering Design	**Similarities**	**Scientific Method**
• Purpose: **Designing** solutions for real world problems. • Works with the **artificial** world. • Creates a tangible product. • Builds a prototype • **Recreates** the world	• Cyclical processes (iterative) • Identify a problem or question • Background research • Make observations • Test • Collect Data • Communicate findings • Flexible and fluid processes	• Purpose: **Discovering** information about the natural world • Works with the **natural** world • Often follows a specific procedure • Answers an investigative question • **Describes** the natural world

As indicated in Table 4, some similarities between the processes include, both are iterative and involve making observations. Some differences unique to engineering design are that engineers use the engineering design process to design solutions for real world problems and often build prototypes. Conversely, scientists use the scientific method to discover information about the natural world and often answer investigative questions. This discussion was an important step in the intervention because research indicates that students struggle to make connections between science and engineering practices (Berland et al., 2014; Crismond, 2001). By explicitly discussing these similarities and differences, students can see how science and engineering design processes are related as well as their unique differences.

After formal introduction to the engineering design process, students were presented with the specific engineering design challenges. Across all classrooms, the students then attempted to solve the design challenges by working through the steps in the engineering design process (see Figure 4). During these EDIS units, students worked both individually and in groups. After providing interactive instruction in the beginning of the unit to explain the engineering design process and the design challenge, teachers shifted to the role of facilitator while students were creating their design solutions. In all EDIS units, students created physical models or drawings of their prototypes.

Below is an example EDIS unit (*Cleaning Up Oil Spills*) that one of the pre-service teachers, Tess, taught in her high school earth science class. The duration of the unit was one 90-minute class period. In her unit plan, Tess addressed both science and engineering design learning objectives. For instance, in one set of learning objectives she stated that students will (a) know that oil can end up in freshwater resources through non-point pollution and (b) apply the engineering design process to solve the problem. Additionally, Tess listed state standards and NGSS practices addressed by the lesson, which cover both science and engineering design content (see Table 5).

Table 5. Example EDIS Unit – Cleaning Up Oil Spills

Standards / Practices		Specific connections to classroom activities
VA SOL	ES.8 The student will investigate and understand how freshwater resources are influenced by geologic processes and the activities of humans. Key concepts include d) identification of sources of fresh water including rivers, springs, and aquifers, with references to the hydrologic cycle e) the dependence on freshwater resources and the effects of human usage on water quality	During the initial stages of the engineering design process, students engage in a classroom discussion regarding freshwater resources and run-off. Throughout the activity, students engage in designing devices and systems to remove oil from a polluted water source. Students observe that there are no "perfect" methods, and thus it is important to take precautionary measures to prevent pollution.
NGSS Practices	Developing and Using Models	Students create models of tools used to clean up oil spills.
	Planning and Carrying out Investigations	Students are provided with a design journal in which they are to detail their observations and findings as they progress through the engineering design process.
	Analyzing and Interpreting Data	Students analyze the data from their testing to determine the effectiveness of their design.
	Constructing Explanations and Designing Solutions	Throughout the activity, students are designing a solution for how to best clean up oil spills.
	Engaging in Argument from Evidence	Students work in groups and must advocate for their ideas using evidence from testing. Additionally, students support their conclusions with data and evidence.
	Obtaining, Evaluating, and Communicating Information	Throughout the engineering design process, students gather data and record it in their design journals. Then through oral and written communication, students relay their findings.

Note: VA SOL= Virginia Standard of Learning; NGSS = Next Generation Science Standards

At the beginning of the unit, students took the Science Content Knowledge (SCK) and Student Understanding of the Engineering Design Process (SUEDP) pre-tests and the

Perceptions of Engineering Design (PED) pre-survey. Next, the pre-service teacher introduced the engineering design process to students using interactive presentation (see Figure 4 above). The students were then presented with the following design challenge, *"Oh no! A major rainstorm has washed a lot of road runoff into Lake Allegheny. The lake is now shiny with dark oil. You are part of a cleanup crew from the Department of Environmental Quality tasked with removing as much of the oil from the water as possible."* Students then engaged in the subsequent steps of the engineering design process. First, they identified the underlying problem present in the design challenge, and then they conducted background research. Next, they created various systems using the tools provided to remove the oil from their water container. All of the tools provided were representations of actual implements used to clean up oil spills in real life. Students were given a "budget" with which they could purchase cleaning tools. After groups attempted to remove all of the oil from the water, they put their "cleaned" water through a series of tests to determine the effectiveness of their solution. Students then shared their designs with classmates and discussed potential ways that they could redesign their system. At the conclusion of the unit, students completed the SCK and SUEDP post-tests and the PED post-survey.

Data Collection Instruments and Procedures

Data collection instruments were developed by the research team involved in the National Science Foundation (NSF) project in which this dissertation study was conducted. Reliability and validity measures for the instruments were assessed. In general, a reliability estimate is essential in order to determine whether or not the scores produced by the test or survey are reliable. More broadly speaking, the Classical Test Theory suggests that if an individual were to take the test an infinite amount of times, the average of their scores would equal their "true" score, with each individual score holding some amount of measurement error (Traub & Rowley, 1991). A reliability estimate describes the "percentage of observed variance in scores due to systematic differences in examinee performance" (Traub & Rowley, 1991, p.5). There are several types of reliability estimates, some of which require participants to take the exam multiple times (i.e. alternative forms or test-retest). However, in this study, Coefficient alpha was computed to determine the internal consistency of the instruments. Coefficient alpha ranges from 0-1, with a higher score indicating that items relate well together (Cronbach, 1951). Stated another way, a high Coefficient alpha value suggests that the observed score variance is more dependent on the true score variance as opposed to measurement error.

Additionally, validity "the evidence presented to support or refute the meaning or interpretation assigned to assessment results" is an important psychometric that must be examined (Downing, 2003, p.830). While there are several types of evidence for validity (i.e. construct, content, and criterion), the primary sources of validity evidence for the instruments in the current study is content related and construct related validity. Measures of reliability and validity of these instruments are discussed below.

Student tests. Both the Science Content Knowledge (SCK) and the Student Understanding of Engineering Design Process (SUEDP) tests were paper and pencil tests for the following three reasons: (1) if taking the tests on the computer, students may look up the answers, (2) computer and internet access may not be reliable in all classrooms where the study was conducted, and (3) paper and pencil allows students to draw diagrams to convey their ideas. Both tests had open-ended items. Thus, students were not constrained by answer choices and were encouraged to write as much as they wanted. However, there were some limitations to this method such as students leaving questions blank and students potentially writing slower than they type and thus providing less information.

Science Content Knowledge (SCK) test. Science content test questions were developed through collaboration between the pre-service science teachers and the researchers (see Appendix A). Each pre-service teacher created 3-5 overarching content specific, open-ended questions based on the science learning objectives of their EDIS unit. For each SCK instrument, Cronbach's alpha was calculated to determine the internal consistency of the instrument (Table 6). While some of the SCK assessments demonstrated a moderate amount of internal consistency (i.e. Marissa α=.75 & Robert α=.71), while others are below the threshold values (i.e. Beth α=.53 & Theresa α=.26) (Nunnally & Bernstein, 1994).

Table 6. Internal Consistency of Each SCK Assessment

Pre-Service Teacher	Cronbach's Alpha
Abigail	.69
Beth	.53
Marissa	.75
Mark	.46
Mary	.63
Robert	.71
Samantha	.54
Tess	.60
Theresa	.26

Student Understanding of Engineering Design Process (SUEDP) test. The science methods instructor developed this test using the *Framework for K-12 Science Education* and *NGSS* (NRC, 2012; NGSS Lead States, 2013) (see Appendix B). The six primary questions include: (1) *What is engineering?* (2) *Describe the engineering design process.* (3) *Is the engineering design process linear or cyclical? Explain your answer.* (4) *What is the difference between the scientific method and the engineering design process?*

(5) *What is a design challenge in engineering?* and (6) *What is a design solution in engineering?* Two additional questions were added to the post-test, in order for students to reflect on their experiences. These reflection questions were (1) *What did you like most about the engineering design process?* and (2) *How did the engineering design process help you to learn more about [insert science topic]?* The second question was tailored to reflect the individual science content present in each pre-service teacher's unit. The additional two reflection questions were used solely in the second phase of analysis to qualitatively look for themes.

In order to assess the psychometrics of the six-item instrument, several analyses were run following the coding of the data (see Data Analysis for coding scheme). First using the pre-test data, Cronbach's alpha was used to determine the internal consistency of the instrument. Results from the analysis indicate that there was only one case with missing data, and the descriptive statistics revealed that the skewness and kurtosis for all of the assessment items were within the acceptable limit of <1.0, with the exception of item 1. Cronbach's alpha was computed to be 0.79, which is above the range of what is considered to be acceptable (Nunnally & Bernstein, 1994). Since student responses to the items are coded as categorical variables, Spearman's Rank Correlation was used to examine the relationship between the items in the instrument. Spearman's rho is preferred over Pearson's correlation for discrete data (May, Masson, & Hunter, 1990, p.138). As indicated in Table 7, all items are statistically significantly correlated with each other.

Table 7. Spearman's Correlation Values for SUEDP Items

Instrument Items	SUEDP 1	SUEDP 2	SUEDP 3	SUEDP 4	SUEDP 5	SUEDP 6
SUEDP 1	--					
SUEDP 2	.29**	--				
SUEDP 3	.24**	.52**	--			
SUEDP 4	.28**	.47**	.42**	--		
SUEDP 5	.24**	.44**	.42**	.45**	--	
SUEDP 6	.23**	.39**	.45**	.43**	.62**	--

Note. SUEDP = Student Understanding of Engineering Design Process
***Significant at p<0.01.*

In order to examine the factor structure of the six-question instrument, an exploratory factor analysis (EFA) was performed. Specifically, a principal axis factor extraction was run. Prior to running the factor analysis, the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy, and the Bartlett's test of sphericity were conducted to determine if the data met the minimum standard for performing the factor analysis. The KMO value for the sample (KMO =.82) indicated that the strength of the relationship amongst the items was more than sufficient and above the suggested minimum value of .60 (Dziuban & Shirkey, 1974). Furthermore, results of the Bartlett's test of sphericity, were statistically significant (χ^2 (15)=706.94, p<0.000) indicating that the factor analysis was appropriate (Dziuban & Shirkey, 1974).

Based on Kaiser's rule of eigenvalues greater than 1.0, the results in Table 8 suggest a single factor solution, which accounts for 48.89% of the variance observed in the scores. This was further verified upon observing the scree plot and the factor loadings (see Table 9).

Table 8. Principal Axis Factor Extraction for SUEDP Instrument

	Initial Eigenvalues		
Factor	Total	% of Variance	Cumulative %
1	2.93	48.89	48.89
2	.86	14.31	63.21
3	.74	12.25	75.45

Note. SUEDP = Student Understanding of Engineering Design Process

Table 9. Factor Loadings for Unrotated Solution

Item	Factor Loading
SUEDP 5: *What is a design challenge in engineering?*	.69
SUEDP 2: *Describe the engineering design process.*	.67
SUEDP 3: *Is the engineering design process linear or cyclical? Explain.*	.66
SUEDP 6: *What is a design solution in engineering?*	.65
SUEDP 4: *What is the difference between the scientific method and the engineering design process?*	.64
SUEDP 1: *What is engineering?*	.39

Note. SUEDP = Student Understanding of Engineering Design Process

Overall, when determining the number of factors to retain the following criteria were considered: Kaiser's rule of eigenvalues greater than 1.0, Cattell's scree plot requirements, the amount of variance accounted for by individual factors and the overall solution, factor loadings, and internal consistency (Cattell, 1966; Curran, West, & Finch, 1996; Kaiser, 1960). Thus, the clear simple structure in the unrotated solution along with the internal reliability results indicate that the six item SUEDP instrument represents a single factor, which we have elected to categorize as engineering design knowledge.

Additionally, the results of the factor analysis serve as evidence for construct validity by ensuring that the expected relationship amongst the latent traits and items exists. Furthermore, the instrument was developed by a content expert and grounded in the literature which provide evidence to support the content validity of the instrument.

Perceptions of Engineering Design (PED) survey. The student perceptions of engineering design (PED) survey was created by the project Principal Investigator (PI) in which this study was conducted. The ten items included statements about engineering design process, to which students responded on a 5-point Likert scale spanning from strongly disagree to strongly agree (see Appendix C). Example statements are as follows: "*I like using engineering design to learn science*", "*I would rather do engineering than regular science*", and "*I am very comfortable designing engineering projects in science lessons.*"

Due to the fact that the instrument was developed for this study by the researchers, there is a need to test the psychometrics of the instrument. First, the reliability of the overall instrument was assessed using the internal reliability statistic of Cronbach's alpha calculated from students' pre-assessment responses. The Cronbach's alpha of 0.86 suggests that there is a strong internal reliability amongst the items in the assessment. As a result of the 5-point Likert-scale responses, Spearman's correlation was used to determine the relationship between individual items. Upon examining the results in the correlation matrix, it became evident that all of the items, except for item 6, were statistically significantly correlated with each other (See Table 10).

Table 10. Spearman's Correlation Values for PED Items

Item	PED1	PED2	PED3	PED4	PED5	PED6	PED7	PED8	PED9	PED10
PED1	--									
PED2	.64**	--								
PED3	.70**	.65**	--							
PED4	.53**	.39**	.54**	--						
PED5	.44**	.46**	.42**	.54**	--					
PED6	.04	.07	.06	-.04	.04	--				
PED7	.40**	.43**	.40**	.25**	.34**	.01	--			
PED8	.51**	.46**	.49**	.42**	.42**	-.01	.50**	--		
PED9	.45**	.41**	.45**	.33**	.35**	.01	.46**	.67**	--	
PED10	.38**	.37**	.43**	.33**	.35**	.24**	.24**	.33**	.33**	--

Note. PED = Perceptions of Engineering Design
***Significant at p<0.01.*

The goal of the instrument was to measure only one construct, students' perceptions of engineering design. Thus, an exploratory factor analysis was performed on the pre-assessment data to examine the factor structure of the instrument. Prior to running the factor analysis, the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was found to be .88 and Bartlett's test of sphericity was statistically significant (χ^2 (45) =1756.29, p<0.000) indicating that the factor analysis could progress (Dziuban & Shirkey, 1974). Results from the initial principal axis factor extraction are presented in Table 11 below and indicate a two-factor solution based on Kaiser's rule of eigenvalues greater than 1.0 (Kaiser, 1960). However, the second factor only accounts for 11% of the variance amongst the scores, and when examining the factor loadings, only one item, item 6, loads onto the second factor.

Table 11. Initial Principal Axis Factor Extraction for PED Survey

	Initial Eigenvalues		
Factor	Total	% of Variance	Cumulative %
1	4.74	47.42	47.42
2	1.12	11.16	58.59
3	.96	9.58	68.17

Item 6 was suspected to be problematic due to its wording – "*Learning science through engineering design has not changed some of my ideas about how the physical world works*". This item is negatively worded, and while there is one other such item, item 10, item 6 does not have the word "not" bolded and capitalized to show emphasis like item 10 does. For this reason, along with the results of the reliability in which the item did not relate to other items (see Table 10) and EFA analyses (see Table 11), item 6 was dropped from the instrument.

Next, the EFA was re-run without item 6. Results from the principal axis factor extraction suggest one factor, which accounts for 52.39% of the variance amongst scores (Kaiser, 1960). The one factor solution is further supported by the factor loadings indicated in Table 12. Additionally, when using a 9-item assessment, the overall Cronbach's alpha is .88, which indicates a high degree of internal consistency.

Table 12. Factor Loadings for Unrotated Solution for PED Survey

Item	Factor Loading
PED 3: *Engineering challenges are fun.*	.82
PED 1: *I like engineering.*	.79
PED 2: *I like using engineering design to learn science.*	.75
PED 8: *I am very comfortable designing engineering projects in science lessons.*	.72
PED 9: *I am confident in my ability to use engineering design skills to reason logically about the physical world.*	.66
PED 5: *I learn more science when using engineering design.*	.65
PED 4: *I would rather do engineering than regular science.*	.63
PED 7: *it is easy for me to explain how science concepts apply in everyday life through engineering design.*	.58
PED 10: *Engineering design is* ***NOT*** *an effective tool for learning science.*	.50

Note. PED = Perceptions of Engineering Design

Support for the validity of the instrument can be found in both construct and content related evidence. For instance, the factor analysis helps to support the argument for construct validity suggesting that all items are measuring a single construct. Furthermore, the PI of the project and a content expert in this field developed the instrument, which was also informed by the literature.

Engineering design integrated science units. Prior to teaching their EDIS units, pre-service teachers submitted their unit plans to the course instructor for review. The following elements were consistent across all pre-service teachers' units: appropriate Virginia Standards of Learning (VA SOLs) and NGSS, materials and resources needed for the lessons, an outline of all of the steps of the EDP and corresponding student and teacher tasks, and student assessments. Pre-service teachers also submitted all instructional materials including student handouts and presentation slides for review.

Classroom observations. Engineering design integrated science lessons were videotaped and observed by the researcher. While the EDIS units varied in their length (90-540 minutes), all units span at least the entirety of one 90-minute class period. Additionally, some teachers taught the same unit across different blocks of students. Therefore, the quantity of observational data varies amongst pre-service teachers. One of the researchers conducted classroom observations, took detailed field notes (see Appendix D). Field notes contained information such as instructional practices, directions provided to students, student activities, and conversations between the pre-service teacher and the students. In addition to detailing what was observed, the researcher provided analytic notes to convey inferences made during the observation process. Since the identification of the exemplar classroom was unknown at the time of the EDIS implementation, many of the class periods of the pre-service teachers were observed during the intervention. However, during the data analysis, only the field notes from the selected exemplar classroom were qualitatively analyzed.

Pre-service teacher semi-structured interviews. After teaching their EDIS lesson, pre-service teachers were interviewed using a semi-structured interview protocol (see Appendix E). The researcher who observed the lessons conducted the interviews with pre-service teachers. All interviews were audiotaped and transcribed. Interviews lasted on average of 20 minutes long. Pre-service teachers were asked to reflect upon the implementation of their EDIS lessons. The following questions focused on how well pre-service teachers viewed their implementation: *(a) To what extent did your EDIS instruction proceeded as planned? (b) How (if at all) do you think engineering design helped the students to better learn science content in your EDIS unit? and (c) If you were to teach this unit again, what (if anything) would you do differently?* One advantage of the interviews was that it allowed for pre-service teachers to describe their responses unconstrained by writing. Furthermore, the researcher was able to ask clarification questions to the participants' responses. One of the limitations of the interviews was that the researcher was also involved in the pre-service teachers' methods course. This may result in participants displaying social desirability bias. While all pre-service teachers were interviewed as part of the larger NSF project, only the interview from the exemplar classroom was qualitatively analyzed.

Data Analysis

Following the sequential explanatory mixed methods design (Creswell & Clark, 2011), there were two phases of analysis. First, the quantitative phase, consisted of transforming some of the qualitative data into quantitative data and analyzing the data using descriptive statistics, dependent sample t-tests. Then, hierarchical linear modeling and multiple regression were employed to examine student learning outcomes in light of the OTL theoretical framework. The quantitative analysis in phase 1 resulted in the identification and selection of one exemplary pre-service science teacher and her classroom to further examine in phase 2. Data analysis phase 2 consisted of the qualitative analysis of an individual pre-service teacher and her classroom. The purpose of the in-depth examination into the exemplar classroom served two purposes: (1) to create a detailed and rich picture of the instructional planning an implementation of an EDIS unit plan that provided students with a high Opportunity to Learn environment and (2) to identify potential explanations for the learning gains reported in the quantitative analysis.

Phase 1: Data Coding

The purpose of the quantitative analysis is to determine the extent to which pre-service teachers' EDIS instruction impacted student learning outcomes, as measured by the SCK test, SUEDP test, and the PED survey, with an additional focus on the way in which the OTL framework may influence student learning outcomes. During phase 1, much of the raw qualitative data (e.g. student responses on the SCK and SUEDP tests and unit plans) was coded. This allowed for both quantitative and qualitative data sources to be used as teacher and student level factors in the multi-level model.

Student tests. For the science content knowledge and understanding of engineering design process tests, the lead PI and I created scoring codebooks. Because all students took the same 6-item SUEDP test, the SUEDP codebook was the same for each pre-service teacher. Student responses were compared to the codebook and were coded as either 2-correct, 1-partially correct, or 0-incorrect or left blank. For instance, in response to the test item, "*Describe the engineering design process. Use a diagram to illustrate your answer*", the following answers were coded as a 1 (see Figure 5). In both examples, the students have indicated some understanding of the engineering design process. Both depict a process in which there is a plan, that is then enacted through the creation or building of something. However, both fail to indicate that the EDP is cyclical with the potential for redesign, and thus, they both received a code of 1-partially correct.

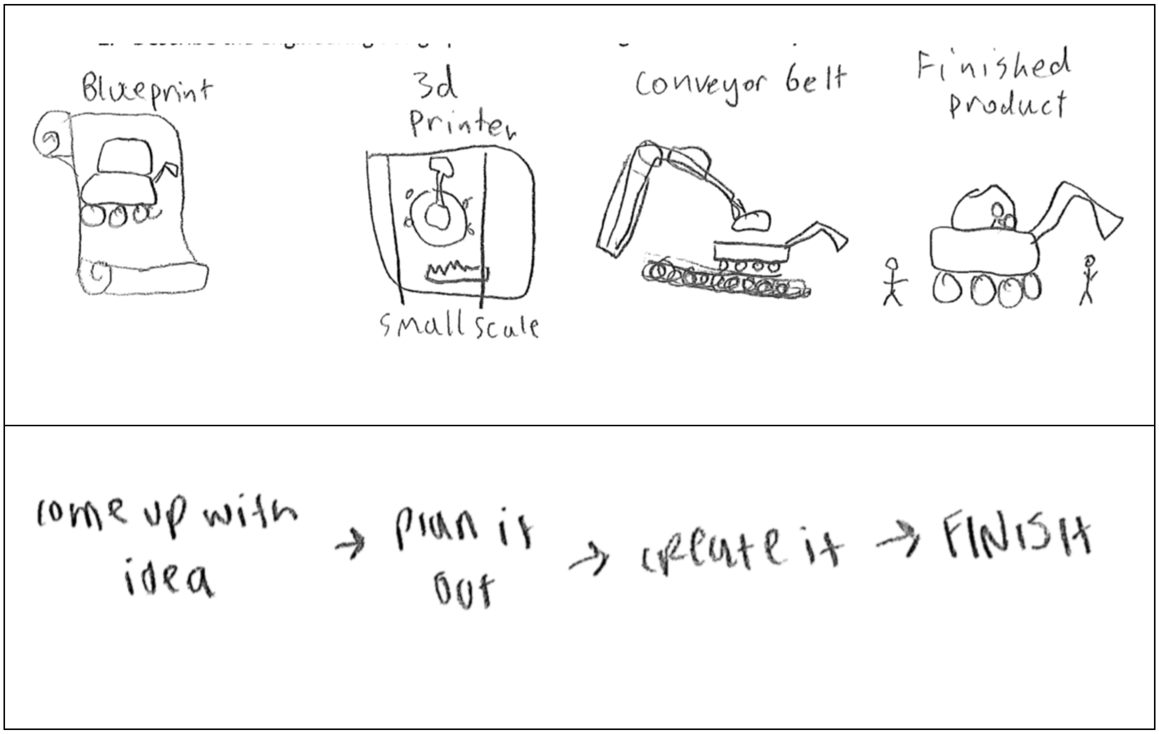

Figure 5. Sample Student Responses to "Describe the Engineering Design Process" that Received a Code 1

Three examples of student responses that received a code of 2-correct are provided below (see Figure 6). These answers received full points for several reasons. First, they provided a general list of many of the steps in the engineering design process. Since there are many versions of the engineering design process, students did not have a to have all of the steps of one particular model, but rather had to provide several steps which depicted an understanding of the basic problem identification, design, test process. Furthermore, all three responses included an indication that the students understood the process to be cyclical. The first two responses indicated the cyclical nature of the process by including the steps of "redesign" or "improve" and by placing the steps in a circle. The last response indicates that the process is on-going by including the "modify" step and an arrow indicating a continuation of the process.

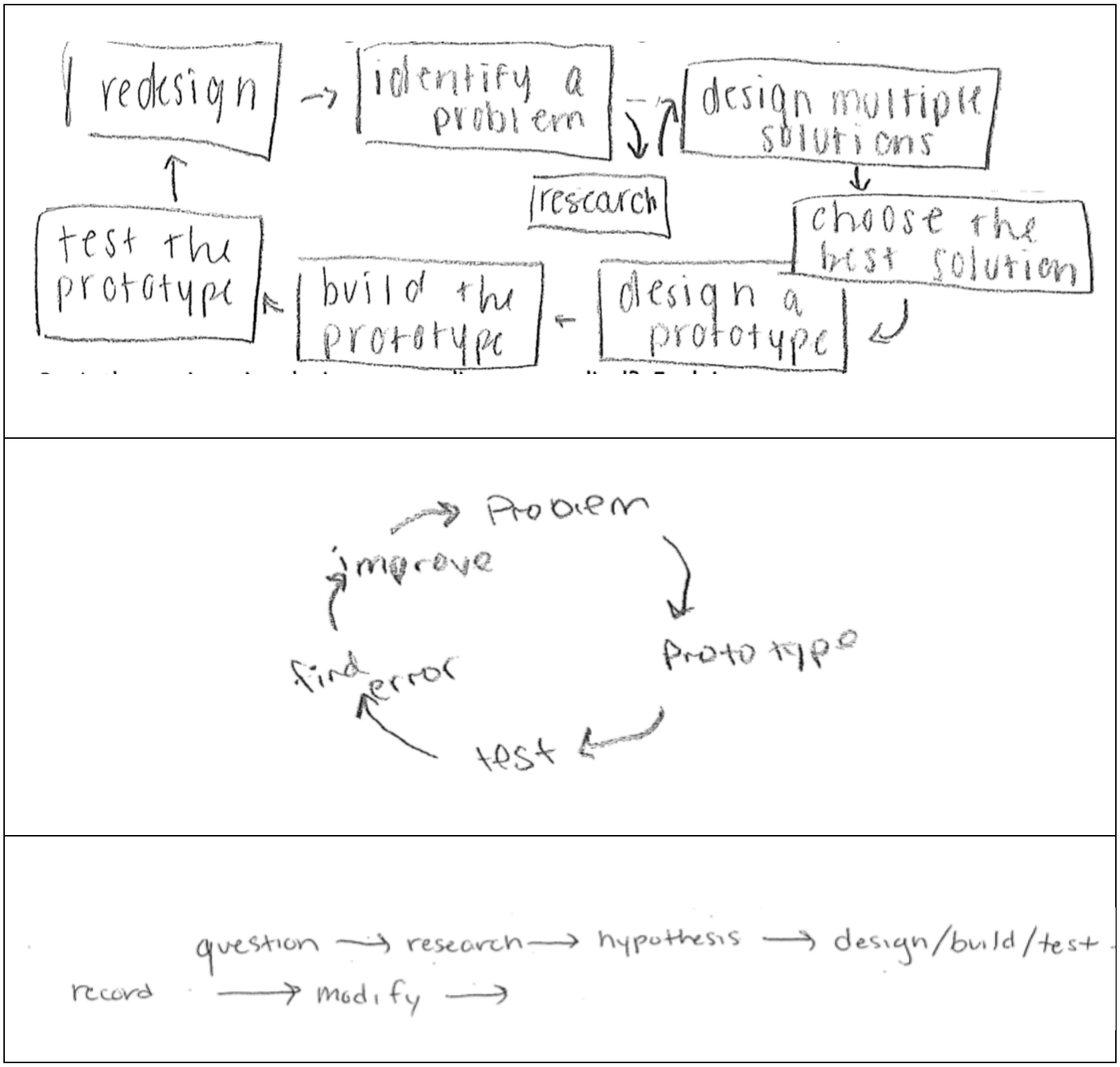

Figure 6. Sample Student Responses to "Describe the Engineering Design Process" that Received a Code 2

For the science content knowledges tests, individual codebooks were created for each pre-service teacher due to the varied content across the EDIS units. An example of part of one of the science content knowledge codebooks is provided in Figure 7.

Item	0 (Completely off topic) Completely off topic I don't know ?	1 (Partially Correct/ Misconceptions) Partially correct -- wrong ideas (a misconception or any wrong information even if other parts are correct)	2 (Completely Correct) Include some of the following information
1. What is diffusion?	Completely off topic I don't know ?	Spreading of molecules/ substances Passing through the cell membrane Misconception – diffusion is the splitting/ breaking of cells (mitosis) Diffusion as related to the term fusion – two things merging into one or as the opposite of fusion (taking things apart)	Movement of molecules (substances, things) from high concentration to low concentration. Without energy
2. What type of molecule makes up most of the cell's plasma membrane?	Completely off topic I don't know ? Plasma	Proteins (channels) Cholesterol Macromolecules Bilayer Cell parts (cytoplasm)	Phospholipids (lipids)

Figure 7. An Excerpt from the Creating Cell Membranes SCK Test Codebook

Two researchers, myself and a graduate student who is familiar with EDIS instruction, coded all of the SCK and SUEDP data independently. Krippendorf's Alpha was used to measure inter-rater reliability and to ensure that the raters have a high rate of agreement (Krippendorf, 2013). A comparison of the initial codes resulted in a Krippendorf's Alpha of .89 for the SCK, and .88 for the SUEDP. After the initial round of coding, the two coders discussed each discrepancy in coding and resolved the differences to obtain 100% agreement. When necessary, clarifications of descriptions were added to the codebooks.

Students' Perceptions of Engineering Design (PED) survey. The student perceptions of engineering assessment will provide quantitative scores on a 1-5 Likert scale. Reverse coding was necessary in order to ensure that the lower scores indicate more negative perceptions of engineering, and higher scores indicate more positive perceptions of engineering.

After coding, an average for each subtest, SCK, SUEDP, and PED, was calculated for each student for both their pre and post-tests. The pre-test scores were used as predictor variables in the overall model as described below. A strength of this data source is the large sample size. Descriptive analyses and t-tests were conducted to determine if there are any differences between the pre and post-test scores for the science content, engineering design, and student perceptions of engineering survey. Additional preliminary t-tests were conducted to determine if there are any statistical differences in post scores across classes.

Opportunity to learn measures. There are many ways to measure the three components of the OTL framework (time, content coverage, and quality). And thus, it is acknowledged that while there may be other more comprehensive measures, this study presents one such way of quantifying these constructs. For example, the quality measure is assessed through an examination the unit plans. The unit plans were analyzed in two ways. First, the degree of integration between the science and engineering design content in the unit plan was determined, and then the quality of the unit plan was analyzed.

Content coverage. According to the OTL framework (Kurz, 2011), content coverage pertains to the degree to which the content taught is aligned with the content assessed. In this study, the content assessed covers both science and engineering design. Thus, the instructional planning should contain comprehensive coverage of both the science content and the engineering design content. Furthermore, research suggests that the degree of integration between the science and engineering design content might impact student learning outcomes (Crotty et al., 2017; Guzey et al., 2017a). Therefore, one assumption of this study is that if (a) science and engineering design content are equally assessed and should be equally represented in instruction (as determined by OTL) and (b) the literature suggests that a balanced integration may promote the greatest student gains, then the degree of integration between the two content areas can be used as a potential measure of content coverage.

To assess content integration, unit plans were categorized based on "*The Continuum Model for Engineering Design and Science Integration*" (Mumba et al., 2017). While this model is undergoing validity testing, it is a helpful way to assess the degree of engineering and science practices present in a unit. The model contains the following five categories progressing from engineering only lessons to science only lessons; Independent Engineering Design Activity, Engineering Design Focus Activity, Balanced Engineering Design & Science Activity, Science Focus Activity, and Independent Science Activity (see Figure 8). Thus, for the variable "content coverage" each unit plan received a code 1-5 corresponding to the categories. It is important to note that the categories are not ordinal. Two coders independently read through the totality of each unit plan and corresponding instructional materials to determine the degree to which each unit plan was integrated. The coders initially had 89% agreement in the categorization of the unit plans, with differences in the coding of one unit plan. The coders discussed the differences and reached agreement for the code.

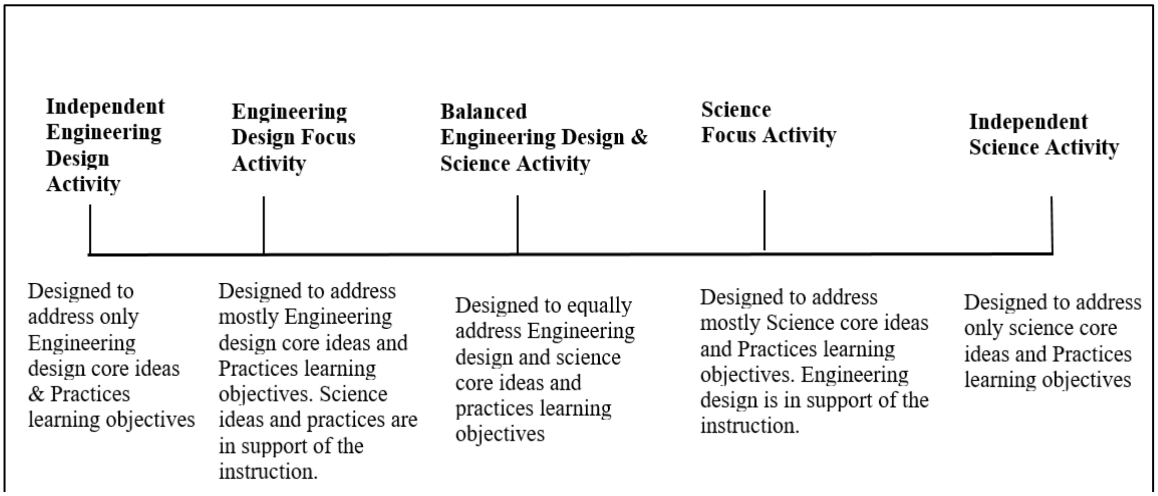

Figure 8. A Continuum Model for Engineering Design and Science Integration (Mumba et al., 2017)

Quality. Quality of instruction is another component of the OTL framework. Additionally, since each pre-service teacher created or adapted their own engineering design integrated science unit, there is a need to capture the variation in the quality of these unit plans. While ideally the enacted EDIS units would be examined for quality of instruction, practical constraints (e.g. multiple coders, time, and resources) limited the scope of analysis to the EDIS unit plans. Therefore, it should be noted that the quality of the EDIS unit refers to the intended curriculum and not the enacted curriculum.

To assess the quality of the curriculum created by pre-service teachers, their unit plans and instructional materials were evaluated using the curriculum evaluation tool created by Guzey et al. (2016a) (see Appendix F). A strength of the instrument is that it was developed based on a comprehensive literature review and alignment with the Moore et al. (2014) STEM integration framework. Within this rubric, there are nine specific ratings and one overall rating. For the present study, one specific rating – integration of math content – was eliminated because math integration was not the focus of the engineering design integrated science unit plans. The remaining eight specific ratings are as follows: *(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 of the specific components of the rubric was evaluated on a 0-4 scale, with 0 representing not present and 4 representing excellent. Each specific rating included probing questions designed to focus the rater. Both raters independently scored each of the eight specific components and provided a justification for their ratings. Additionally, an overall rating was determined for each pre-service teacher. Following the independent coding, the raters compared codes and for the overall codes obtained an inter-rater reliability score of approximately 55%, which then necessitated additional meetings between the coders and revisions were made to the scoring rubric. Next, the two raters discussed all differences in coding and resolved any differences to achieve 100% inter-rater reliability.

Time. Initially, within the concept of the Opportunity to Learn (Carroll, 1963), time was defined as the quantity of time allocated for learning. Since then, many researchers have narrowed this description to specifically refer to engaged time or instructional time (Kurz, 2011, p.109). For the purposes of this study, time will refer to the actual amount of instructional time dedicated to the implementation of the EDIS unit. While, many of the pre-service science teachers did adhere to the amount of time predicted in their EDIS unit plans, some pre-service teachers extended their lesson beyond the time initially planned for. In such cases, the actual amount of time spent on the unit was used. Time was reported in minutes due to the variation in class period length across participants (see Table 13).

Table 13. Unit Length of EDIS Units Taught (min)

Pre-Service Teacher	EDIS Unit Title	Unit Length (min)
Abigail	Cheetos Engineering	130
Beth	Building Synthetic Tissues	360
Marissa	Saving the Bees	90
Mark	Engineering Potatoes	315
Mary	Creating Cell Membranes	315
Robert	Bottle Rockets	270
Samantha	Cookie Mining	90
Tess	Cleaning Up Oil Spills	90
Theresa	Containing Slime Molds	360

Phase 1: Quantitative Analysis

Missing data. As previously mentioned, when coding the SCK and SUEDP tests, when individual assessment items were left, blank, they were coded as a 0. If students left items blank for the PED survey, they were coded as individually missing items. This was done in an effort to avoid biasing a student's average score, since the Likert scale ranged from 1-5 and unlike with the content assessments, a blank item on a perceptions assessment could not be assumed to indicate a lack of understanding. Because the quantitative analysis depended on having both pre and post-test scores for each unit of analysis, students missing either the entire pre-test or post-test were removed from the analysis. Prior to the removal of cases, there were 530 high school students in the sample. There were 70 cases of missing data, which resulted in 13.2% of the cases being removed, leaving a total sample of 460 high school students. This is within the acceptable range of missing data (Enders, 2003). While it is impossible to know for certain, it is hypothesized that the missing data is "missing at random" and that those who were not present for the pre or post assessments would score no differently than their peers. With this assumption, no further adjustments needed to occur to account for the missing values (Allison, 2001). Table 14 illustrates the number of missing cases by pre-service teacher.

Table 14. Cases of Missing Data by Pre-Service Teacher

Pre-Service Teacher	Number of missing cases (Pre-test)	Number of missing cases (Post-test)	Number of students (after deletion)
Abigail	2	7	68
Beth	1	6	54
Marissa	9	0	12
Mark	0	0	15
Mary	5	8	107
Robert	3	8	33
Samantha	2	7	42
Tess	1	6	58
Theresa	2	3	71

It is important to note that because all three assessments were given at once, if a student left one or two of the assessments blank, but answered at least one question on one assessment, they were retained and their blank responses were coded as either 0 for SCK and SUEDP items or as missing for PED items. Thus, due to the coding scheme mentioned above for the PED survey, some students did not have a PED overall score, and as a result pairwise deletion was used when running the statistical analyses described below.

Statistical analysis. In order to address the first research question, *To what extent does engineering design integrated science instruction situated in an OTL model impact student learning outcomes in science (as measured by science content knowledge) and engineering design (as measured by understanding of engineering design and perceptions of engineering)?*, an overall dependent t-test comparing average pre and post-test scores was run for each of the three student assessments. Next, the data was disaggregated by pre-service teacher, and individual dependent t-tests were performed to determine the impact of engineering design integrated science teaching on student learning outcomes at the individual teacher level. Finally, following the selection of the exemplar class, dependent t-tests were conducted at the item-level of each sub-test for the following two reasons: (1) to ensure that the learning outcomes in the case study mirrored the overall quantitative results and (2) to provide specific insight into what the students in a particular classroom learned at the item level following EDIS instruction. Assumptions for the dependent t-test, normality of the distribution, homogeneity of variance, and independence, were examined prior to running the analyses (Lewis-Beck, Bryman, & Liao, 2003, p.351).

Hierarchical linear modeling. When analyzing student scores, it is important to account for the nested nature of the data, students within pre-service teachers' classrooms. While all of the pre-service teachers were trained in the same intervention, practically there were many observed differences across classrooms such as the science content taught and the quality of the lesson plans. As such, hierarchical multi-level modeling (HLM) was used to estimate the variation amongst student scores accounting for different teachers (Raudenbush & Bryk, 2002). In turn, this helped to further address research question 1 in looking at exposure to EDIS units and its influence on student learning outcomes. This model has level 1 (students) and level 2 (teacher). Each outcome, Science Content Knowledge, Student Understanding of Engineering Design Process, and Perceptions of Engineering Design, has its own model. The predictor variables, along with their data sources, are listed in Table 15. While the model was initially run with the predictor variable of time, due to the fact that the variable did not contribute any meaningful explanation of variance and often caused warning messages within the software program, the Time variable was dropped from the final HLM model.

Table 15. Hierarchical Linear Modeling Predictor Variables

Name	Level	Data Source	Coding Scheme
Content Coverage	Teacher	Unit Plan	A Continuum Model for Engineering Design and Science Integration (Mumba et al., 2017)
Quality	Teacher	Unit Plan	Curriculum Quality Rubric (Guzey et al., 2016a)
Time (min)	Teacher	Unit Plan / Implementation	N/A
SCK	Student	Pre-test	Coded for accuracy based on 0-2 scale with codebook
SUEDP	Student	Pre-test	Coded for accuracy based on 0-2 scale with codebook
PED	Student	Pre-survey	N/A (5-point Likert scale)

**Note.* SCK=Science Content Knowledge; SUEDP = Student Understanding of Engineering Design Process; PED = Perceptions of Engineering Design

Prior to running the HLM analysis, the following assumptions were tested for; (a) linearity between variables, (b) normality of the variables, as determined by the Shapiro-Wilk's test, (c) homoscedasticity, in which there is homogeneity of variance, and (d) independence of observations.

Next, to determine whether or not a multi-level modeling approach was appropriate, the intraclass correlation coefficient (ICC) was computed to determine the amount of variance in post-test scores attributed to the differences at the classroom level. For the three models corresponding to each learning outcome, the ICC values are as follows: science content knowledge (.29), student understanding of engineering design process (.37), and perceptions of engineering design (.02). There is a somewhat flexible cut-off value of about 0.10, with greater than 0.10 suggesting that there is a moderate amount of variance attributed to classroom level differences (Lee, 2000).

Although, the sample size is small (under 20) for the level 2, based on the ICC for two of the three measures and the need to account for all variance regardless of how small (Gelman & Hill, 2006), the HLM was performed. However, it should be noted that due to the small sample size at the level 2, caution must be taken with the conclusions from the level 2 results due to the potential for estimation biases (Robson & Pevalin, 2016, p.27). With this caveat, the unconditional model with no covariates was run, and then level 1 and level 2 variables were added to estimate the effects of each factor on the outcomes.

Multiple regression. Based on the results of the HLM and the constraints placed on the interpretations of the HLM due to the small level 2 sample size, additional analyses were conducted. Specifically, a multiple regression was performed. This analysis was done to account for the amount of variability in the dependent variable, while using more than one predictor. In this case, the two predictors were student pre-test scores and whether pre-service teachers' units were categorized as well-developed and thus providing a high Opportunity to Learn (OTL) environment or lowly developed, and thus creating a low OTL environment.

OTL grouping. The following steps were taken to determine the categorization of each pre-service teacher's unit as providing either high or low OTL environment. It should be noted that the pre-service teachers' units were evaluated against each other, and therefore a pre-service teacher with a "low OTL environment" in this study, may in fact have a high OTL environment when compared to the general population of science teachers. In order to categorize the units into two groups, the OTL indicators were examined (see Table 16). For each OTL indicator (i.e. content coverage, time, and quality), units were either scored as low (OTL rank = 1) or high (OTL rank =2). For the content coverage, the ideal unit plan would have an equal balance of engineering design and science content because the students are equally assessed in both science and engineering design. This is consistent with previous literature which suggests that engineering design and science should be integrated in a meaningful and explicit way and engineering design should not merely be an “add-on” (Crotty et al., 2017; Guzey et al., 2017a). Therefore, units that were coded as “balanced” received an OTL rank of 2. All other units received a 1. With regards to the time allotted for the EDIS unit, there were two distinct groups – EDIS units that took one 90-minute class period and those that took more than three 90-minute class periods (270 min total). Based on the OTL framework assertion that more time is better for learning the content (at least more than 90 minutes), EDIS units lasting 90 minutes were given an OTL rank of 1 and all others were ranked at a 2. Finally, the codes for the quality of unit plans were examined. Based on the premise that a higher quality unit plan will result in a high OTL environment, those units scoring either a 3 or 4 on the Curriculum Quality Rubric (Guzey et al., 2016a) received a rank of 2 and EDIS units scoring either a 1 or 2 in quality received an OTL rank of 1. Next, each unit received an overall OTL score from the sum of the individual three OTL indicators. Finally, the units were divided into two groups (high or low OTL environment), with those receiving an overall OTL score of 5 or greater categorized as “High OTL Environment, score = 1”, and all others as “Low OTL Environment, score = 0”. Once again, it should be noted that the cut-off is somewhat arbitrary but was selected as such to make comparisons between two groups.

Table 16. Categorization of High OTL and Low OTL Environments

Pre-Service Teacher	Content Coverage Initial Code	Content Coverage OTL Rank	Quality Initial Code	Quality OTL Rank	Time (min) Initial Code	Time (min) OTL Rank	OTL Overall OTL Score	OTL Environment (Code)
Abigail	Balanced	2	3	2	270	2	6	High (1)
Beth	ED Focused	1	2	1	540	2	4	Low (0)
Marissa	Science Focused	1	1	1	90	1	3	Low (0)
Mark	Balanced	2	4	2	315	2	6	High (1)
Mary	Science Focused	1	4	2	315	2	5	High (1)
Robert	ED Focused	1	3	2	360	2	5	High (1)
Samantha	Indep. Science	1	1	1	90	1	3	Low (0)
Tess	ED Focused	1	3	2	90	1	4	Low (0)
Theresa	ED Focused	1	3	2	360	2	5	High (1)

Note. ED = Engineering Design; OTL = Opportunity to Learn

Following the categorization of the units in to the providing a "High OTL Environment/ well-developed" or a "Low OTL Environment/poorly developed" groups, a multiple regression was run for each student learning outcome. Prior to each regression analysis, the following eight assumptions were assessed: (1) continuous dependent variables; (2) two or more independent variables; (3) independence of observations; (4) linear relationship between dependent and independent variables; (5) homoscedasticity; (6) no multicollinearity; (7) no significant outliers, and (8) normally distributed residuals.

Exemplar selection. Once the extent to which learning occurred in science classrooms during EDIS instruction was determined, there remains the question of what occurred within the classroom. An in-depth analysis of a specific exemplar is instrumental in addressing research question 2: "*To what extent does the qualitative data (unit plan, classroom observations, student responses & teacher interview response) from an EDIS* *instruction exemplar, within a high Opportunity to Learn environment, help to explain the quantitative results of student learning outcomes?"* Because of both the nascent stage of EDIS research and the great variation across classrooms in the study (i.e. science content taught, quality of instructional planning, etc.), it is helpful to focus on one particular setting. In an effort to better understand possible explanations for student learning gains, the class was selected based on the following criteria: (1) students demonstrated statistically significant gains in both science and engineering design as measured by the three learning outcomes, (2) across pre-service teachers, this pre-service teachers' students had high post-test scores in both science and engineering design as measured by the three learning outcomes, (3) the pre-service teacher demonstrated a well-developed unit plan as defined by scoring highly on the OTL measures, and (4) the pre-service teacher had a large number of students. See Chapter 5 for a detailed description of the selected EDIS exemplar.

Phase 2: Qualitative Analysis

The purpose of using mixed methods in this study is to employ multiple methods to address the research questions posed. In this study, the role of the qualitative analysis to attempt to further explain the findings provided by the quantitative analysis (Creswell & Clark, 2011) by examining in-depth the context in which they occurred, as well as understanding participant's perspectives of the EDIS unit. A qualitative approach is necessary here because its nature is such that it is "a situated activity that locates the observer in the world" and the role of the researcher is to "study things in their natural settings, attempting to make sense of or interpret phenomena in terms of the meanings that people bring to them" (Denzin & Lincoln, 2011, p.3). As such, engaging in qualitative research provides a deeper and richer picture of what is actually occurring in the classrooms during EDIS instruction in an OTL environment, how participants view their experiences in EDIS instruction, and as a result, what may explain the student learning outcome results.

Exemplar EDIS Unit description. Mary's engineering design integrated science unit was selected based on criteria described above. Mary's unit, "Creating a Cell Membrane", occurred within a high school biology classroom. In order to provide description of the classroom, the unit plan and observation data were analyzed in the following manner. The unit plan was read holistically and examined using the Continuum Model for Engineering Design and Science Integration (Mumba et al., 2017) and the Curriculum Quality Rubric (Guzey et al., 2016a) by two researchers, as mentioned above. Results from this analysis provided the overall structure for the exemplar's instructional planning section. Following the presentation of the unit plan in light of the OTL framework, the observation field notes were analyzed to explain what occurred during the implementation of an EDIS unit which provided a high OTL environment to initially low-performing students. The exemplar pre-service teacher, Mary, taught her EDIS unit to five class sections for four days each. During this EDIS implementation, 18 of the 20 class sessions were observed by the researcher and detailed field notes were compiled. In order to construct a narrative of what occurred during the EDIS implementation, the field notes were first read holistically. Next commonalities in instructional practice and student actions were pulled from across class periods for each day of instruction to provide a cohesive summary of what occurred during the EDIS unit. Next the researcher searched for evidence that may disconfirm the daily summaries. Finally, the researcher included excerpts from Mary's interview to further triangulate the observational data and to allow her voice to be heard.

Participant responses to explain student learning outcomes. The next portion of the qualitative data analysis focused on creating a more complete picture of the EDIS unit. In response to research question 2, all qualitative data sources for the exemplar classroom (the unit plan, observation field notes, interview transcript and student responses to reflective post-assessment questions) were first read holistically without searching for themes. Because the question focuses on the participants' experiences and their explanations of why the learning gains occurred, responses from the two student reflection questions and the pre-service teacher's interview transcript were read again, and each response was coded for an emerging theme. After coding all of the data, the codes were reviewed for potential emergent themes. This process loosely applied the analytic induction technique as described by Erickson (1986) to identify emerging themes from the data. It should be noted that while Erickson (1986) calls for all of the themes to arise from the data completely organically, emergent themes in this study were narrowed to those pertaining to student experiences and potential explanations for their learning outcomes.

Next, the researcher re-examined all of the student response data and the pre-service teacher interview in light of the list of primary themes to ensure that the themes were adequately supported by the data and to create a final list of themes. Then, in an effort to triangulate the data, the observation field notes were read and coded for the list of themes. Throughout this process, the researcher was cognizant of the need to search for disconfirming evidence throughout all data sources. From this process, a list of five salient participant explanations for the learning gains (both content and perceptions) emerged.

Validity criteria. As with any research, there exists the potential for threats to validity to arise. In following Erickson's inductive analytic approach, the researcher attempted to reduce the following five threats to validity as described by Erickson (1986):

inadequate amounts of evidence, inadequate variety in kinds of evidence, faulty interpretive status of evidence, inadequate disconfirming evidence, and inadequate discrepant case analysis.

To address the threat of *inadequate amounts of evidence*, the researcher spent a significant time in the classroom selected for the exemplar. The researcher observed in-person 18 of the 20 class periods in which Mary taught her EDIS unit. The researcher attempted to take detailed field notes, which included thick rich descriptions of what was occurring in the classroom, instructional practices used, instructional materials presented, several student conversations, and dialogue between the pre-service teacher and the students. In addition, when appropriate, the researcher provided inferences of what was occurring in the classroom via analytic notes within the field notes.

In response to the second threat to validity, *inadequate variety in kinds of evidence,* when creating the exemplar description and gathering qualitative themes, four data sources were analyzed: observation field notes, unit plan documents and instructional resources, student responses, and the pre-service teacher interview audio recordings and transcripts. This triangulation of multiple data sources helped to address the third threat to validity, *faulty interpretive status of evidence*. Additionally, the researcher established trust with the pre-service teacher prior to entering her classroom. This strategy was implemented to increase the likelihood of obtaining truthful data from the participant. Furthermore, the researcher engaged in reflexive thinking through the maintenance of a methodological journal throughout the study and in particular, the data analysis phase. In addition, the researcher as instrument statement serves as documentation for the researcher's particular lens. The researcher attempted to reduce the fourth and fifth threats to validity, *inadequate disconfirming evidence and inadequate discrepant case analysis,* by searching the data for disconfirming evidence after creating my themes. Next, the researcher used evidence garnered to reframe the themes.

Overall, the researcher attempted to address threats to validity by grounding her methodological decisions in the literature, using multiple methods, triangulation of data sources, searching for disconfirming evidence, keeping a methodological journal, and the use of multiple coders when coding some of the qualitative data.

Summary

Table 17 below summarizes the research questions, data sources, and analyses.

Table 17. Summary of Research Questions, Data Sources, and Analyses

Research Question(s)	Aim	Data Sources	Data Analysis
RQ #1	To determine the extent to which participation in EDIS units impacts student learning outcomes.	Student Test and Survey Data (Pre and Post) Unit Plans	**Quantitative analysis** t-test comparison of pre and post information HLM to account for the clustering of students within classrooms Multiple regression with OTL groups
RQ #2	To examine in-depth the implementation of an EDIS unit which provides a high OTL environment and to identify potential explanations for student learning outcomes	Student Test and Survey Data (Pre and Post) Unit Plan Observation Field Notes Student Reflection Questions Pre-Service Teacher Interview	**Quantitative analysis** t-test comparison of pre and post information **Qualitative analysis** Thick, rich description of the instructional planning and implementation of an EDIS unit Inductive coding of student responses and pre-service teacher interview to create themes which were then supported by observation field notes

CHAPTER 4: QUANTITATIVE RESULTS

This chapter is organized into three main sections, and its purpose is to address research question 1 through a presentation of the quantitative results. The first section presents overall student learning outcome results across all of the classrooms. The second section uses multi-level modeling and multiple regression to examine the student learning outcomes, in light of the OTL theoretical framework. Based on these results, Mary's EDIS unit was selected as the exemplar. The third section presents the quantitative results of the analysis of the learning outcomes in Mary's class and compares them to the overall sample. Qualitative results used to answer the second research question can be found in Chapter 5.

Student Learning Outcomes

Descriptive Statistics

Prior to running any inferential analyses, descriptive statistics for each of the learning outcomes were computed. Across all classes (n=460), students attained an overall mean pre-test score of 1.06 (*SD*=0.57) on the science content knowledge (SCK) assessment, out of a total of 2 points. Following the EDIS instruction, students on average scored 1.59 (*SD*=0.37). Similarly, a positive trend was seen in the comparison of the Student Understanding of Engineering Design Process (SUEDP) pre-test mean score (μ=0.63, *SD*=.43) and post-test mean score (μ=1.23, *SD*=.44). Furthermore, there was a positive increase in students' perceptions of engineering design (PED) following the implementation of the EDIS units (μ=3.60, *SD*=.70) as compared to before the EDIS units (μ=3.11, *SD*=.69). When examining the data, it is apparent that most of the assessment data is normally distributed (Table 18). However, for some of the assessments, the skewness and kurtosis values were above the commonly accepted value of 1.0 (Hahs-Vaughn & Lomax, 2013). One potential explanation for the violation of normality is the lack of variability within the dependent variables. Both the SCK and the SUEDP tests were scored on a 0-2-point scale and the PED survey consists of a 5-point Likert scale. Despite this, inferential statistical tests were still conducted.

Table 18. Skewness and Kurtosis Values for Assessments

Assessment	Skewness (SE)	Kurtosis (SE)
SCK Pre-test	-.16 (.11)	-.87 (.23)
SCK Post-test	-1.16* (.11)	1.81* (.23)
SUEDP Pre-test	.45 (.11)	-5.84* (.23)
SUEDP Post-test	-.78 (.11)	.33 (.23)
PED Pre-survey	-.09 (.12)	.68 (.23)
PED Post-survey	-.70 (.12)	1.15* (.23)

Note. SCK = Science Content Knowledge, SUEDP = Student Understanding of Engineering Design Process, and PED = Perceptions of Engineering Design
*indicates large values, which suggest non-normality

Dependent T-tests

In order to determine whether or not the learning gains were statistically significant, dependent t-tests were performed for each learning outcome using pairwise deletion to retain as many cases as possible (Table 19). Results indicate that across all classrooms, students demonstrated a statistically significant increase in their knowledge of the specific science content following the engineering design integrated science unit instruction (t_{458}= -19.82, $p<0.000$). Similarly, students' learning of the engineering design process (t_{459}= -24.82, $p<0.000$) and their perceptions of the engineering design process (t_{433}= -17.49, $p<0.000$) were both statistically significant. Overall, this demonstrates that the exposure to the EDIS units resulted in student learning in both science and engineering design outcomes.

Table 19. Student Learning Outcomes

Assessment	Pre-test Mean (SD)	Post-test Mean (SD)	t value(df)	p value
SCK	1.06 (.57)	1.59 (.37)	-19.82 (458)	.000**
SUEDP	.63 (.43)	1.23 (.44)	-24.82 (459)	.000**
PED	3.11 (.69)	3.60 (.70)	-17.49 (433)	.000**

Note. SCK = Science Content Knowledge, SUEDP = Student Understanding of Engineering Design Process, and PED = Perceptions of Engineering Design
***Significant at p<0.001*

The pattern of increased science content knowledge scores in the post-tests as compared to the pre-tests that was observed in the overall sample is also present at the individual teacher level. Table 20 indicates the pre and post-test Science Content Knowledge scores disaggregated by teacher. Descriptively, all classrooms obtained results that were positively trending from the pre to the post-test, which suggests that the EDIS units helped to foster a greater understanding of the specific science content present in the unit. However, the results of the dependent t-test indicate that seven out of the nine classrooms demonstrated statistically significant learning gains (p<0.05) in the science content following exposure to the engineering design integrated science instruction.

Table 20. SCK Test by Individual Pre-Service Teacher

Pre-Service Teacher	Pre-test Mean (SD)	Post-test Mean (SD)	t value (df)	p value
Abigail	1.23 (.37)	1.56 (.26)	-7.54 (67)	.000**
Beth	1.49 (.35)	1.69 (.25)	-4.59 (53)	.000**
Marissa	1.45 (.43)	1.68 (.32)	-2.21 (10)	.052
Mark	.75 (.40)	1.44 (.47)	-6.99 (14)	.000**
Mary	.42 (.33)	1.61 (.36)	-27.76 (106)	.000**
Robert	1.10 (.48)	1.15 (.36)	-.56 (32)	.577
Samantha	1.80 (.35)	1.90 (.24)	-2.59 (41)	.013*
Tory	1.19 (.52)	1.50 (.46)	-5.02 (57)	.000**
Theresa	.99 (.28)	1.62 (.33)	-12.09 (70)	.000**

**Significant at p<.05*
***Significant at p<0.01*

Likewise, a comparison of the results from the SUEDP test indicate that across all pre-service teachers, student scores were trending positively from the pre to the post-test (Table 21). Furthermore, all but one classroom (Tory) demonstrated statistically significant growth (p<0.01) in their understanding of the engineering design process following exposure to the EDIS units. These results suggest that engaging in the EDIS units helped to improve students' understanding of engineering design.

Table 21. SUEDP Test by Individual Pre-Service Teacher

Pre-Service Teacher	Pre-test Mean (SD)	Post-test Mean (SD)	t value (df)	p value
Abigail	.69 (.49)	1.37 (.26)	-11.35 (67)	.000**
Beth	.95 (.42)	1.40 (.29)	-8.65 (53)	.000**
Marissa	.57 (.54)	1.08 (.42)	-3.68 (11)	.004**
Mark	.50 (.34)	1.49 (.18)	-12.29 (14)	.000**
Mary	.49 (.41)	1.49 (.39)	-21.24 (106)	.000**
Robert	.74 (.49)	1.19 (.40)	-6.23 (32)	.000**
Samantha	.43 (.28)	.83 (.39)	-6.79 (41)	.000**
Tory	.69 (.45)	.77 (.42)	-1.56 (57)	.125
Theresa	.67 (.35)	1.25 (.29)	-12.97 (70)	.000**

***Significant at p<0.01*

Lastly, when comparing the pre and post assessment results by individual pre-service teacher, student perceptions of engineering design were higher following the EDIS units for all pre-service teachers (Table 22). Additionally, all but one pre-service teacher had students who demonstrated statistically significant positive changes ($p<.05$) in their perceptions. These results suggest that in all classrooms in which EDIS units were taught, students developed more positive perceptions of engineering design after instruction.

Table 22. PED Survey by Individual Pre-Service Teacher

Pre-Service Teacher	Pre-survey Mean (SD)	Post-survey Mean (SD)	t value (df)	p value
Abigail	3.17 (.60)	3.62 (.60)	-7.39 (61)	.000**
Beth	3.12 (.06)	3.57 (.55)	-6.89 (53)	.000**
Marissa	2.32 (1.30)	3.07 (.62)	-2.11 (10)	.061
Mark	3.05 (.46)	3.59 (.47)	-3.91 (14)	.002**
Mary	3.22 (.66)	3.72 (.56)	-9.16 (97)	.000**
Robert	3.07 (.72)	3.68 (.70)	-5.10 (31)	.000**
Samantha	2.80 (.68)	3.00 (.72)	-2.37 (41)	.023*
Tory	3.25 (.67)	3.60 (.69)	-4.39 (53)	.000**
Theresa	3.03 (.61)	3.56 (.61)	-7.71 (67)	.000**

**Significant at p<.05*
***Significant at p<0.01*

As a whole, these results suggest that exposure to EDIS instruction can improve student learning outcomes in both science (as measured by science content knowledge) and engineering design (as measured by engineering design knowledge and perceptions).

Modeling Informed by the Opportunity to Learn Framework

Though there were positive learning gains occurring across all classrooms and across all three learning outcomes, it should be noted that every teacher planned for and enacted a different EDIS unit plan. And although, it is powerful to note the persistent student learning gains across pre-service teachers, there are some pre-service teachers who have better outcomes than others. Examining the content coverage and quality of the EDIS units, in relation to the learning outcomes is the purpose of the current section.

According to the Opportunity to Learn theoretical framework (Kurz, 2011), there are three crucial components which determine a student's opportunity to learn: content coverage, quality of instruction and time. As previously mentioned in chapter 3, the content coverage, and quality of instruction measures are based on the "planned curriculum", and the time is based on the "enacted curriculum". As stated in the data analysis section in chapter 3 (pages 69-70), all unit plans were coded for their "content coverage" or degree to which they integrated the science and the engineering design content. In addition, the unit plans were analyzed for their quality based on the Curriculum Quality Rubric (Guzey et al., 2016a). For the last dimension of the OTL, time, the amount of time spent on the EDIS unit was determined from the unit plans and the classroom observations, and it was recorded in minutes. Results from the OTL coding of the units along with the post-test scores for each of the student learning outcomes are provided in Table 23. Each of the OTL component and the variation present in the sample is addressed below. It is important to note that while some trends exist between the OTL components and the student learning outcomes, the small sample size restricts conclusions from being drawn.

Table 23. OTL Components and Student Learning Outcomes by Pre-Service Teacher

Pre-Service Teacher	Content Coverage	Quality Score	Time (min)	SCK Mean Post Scores	SUEDP Mean Post Scores	PED Mean Post Scores
Abigail	Balanced	3	270	1.56	1.37	3.67
Beth	ED Focused	2	540	1.69	1.33	3.61
Marissa	Science Focused	1	90	1.69	1.08	3.07
Mark	Balanced	4	315	1.44	1.49	3.64
Mary	Science Focused	4	315	1.61	1.49	3.74
Robert	ED Focused	3	360	1.15	1.19	3.74
Samantha	Independent Science	1	90	1.90	.83	2.98
Tory	ED Focused	3	90	1.50	.77	3.67
Theresa	ED Focused	3	360	1.62	1.25	3.63

Note. ED = Engineering Design; OTL = Opportunity to Learn; SCK = Science Content Knowledge, SUEDP = Student Understanding of Engineering Design Process, and PED = Perceptions of Engineering Design

Content Coverage

In terms of content coverage, only two pre-service science teachers, Abigail and Mark, provided balanced EDIS unit plans according to the Continuum Model for Engineering Design and Science Integration (Mumba et al., 2017). The model defines a balanced EDIS unit plan as one that is “designed to equally address engineering design and science core ideas practices and learning objectives”. Thus, not only must the learning objectives contain balance, but the subsequent unit plan must equally address engineering design and science concepts. The pre-service teachers who developed balanced unit plans had some of the highest post-test mean scores for the SUEDP test (Abigail = 1.39; Mark = 1.49) and the PED survey (Abigail = 3.67; Mark = 3.64). While caution needs to be taken when interpreting results from a small sample size (n=9), results suggest that having a high degree of integration between the science and engineering design content in a unit plan may result in higher engineering design student learning outcomes.

Quality

When looking at the quality of the unit plan, only two pre-service teachers received ratings of 4, which represents "excellent" (see Table 23). These pre-service teachers, Mark and Mary, had students with the highest SUEDP post-test scores (Mark = 1.49; Mary = 1.49) and some of the highest PED post-survey scores (Mark = 3.64; Mary = 3.74). Contrastingly, there were two pre-service teachers with unit plans that received the low-quality score of 1. In addition to having the low-quality scores, these pre-service teachers had students with the lowest mean Perceptions of Engineering Design post-survey scores (Marissa = 3.07; Samantha = 2.98). While conclusive statements cannot be drawn, the results suggest that high quality unit plans provide an environment for higher engineering design student learning outcomes.

Instructional Time

In examining the amount of time spent on the EDIS units, there were three pre-service teachers who had EDIS units lasting at least 360 minutes (see Table 23). Beth's EDIS unit took the most time (540 minutes) and her students had consistently high post-test scores (SCK = 1.69; SUEDP =1.33; PED = 3.61). Surprisingly, two of the three pre-service teachers with the lowest number of EDIS instructional minutes (90 minutes), had students with some of the highest SCK post-test scores (Samantha = 1.90; Marissa = 1.69). While time may impact engineering design learning outcomes, it does not appear to have a linear relationship with science content learning outcomes. Once again, it should be noted that all classes across pre-service teachers demonstrated positively trending results across all three student learning outcomes. Furthermore, due to the small sample size and limited variability of the outcome variables, caution should be taken when parsing out differences between teachers.

Hierarchical Linear Modeling

In order to account for the nested structure of the data when comparing results across teachers, a hierarchical linear model (HLM) was constructed. This model accounts for the nested nature of the data – students within pre-service teachers' classrooms. As mentioned in the data analysis section (Chapter 3, page 75), the model has level 1 (students) and level 2 (teachers), with each student learning outcome depicted in a separate model. Even though the level 2 sample size was small (n=9), the HLM was performed because some statisticians advise that multilevel modeling is always used when in the presence of nested data (Gelman & Hill, 2006, p.246). While initially, all of the OTL measures were included in the model along with the pre-test scores as a covariate, the OTL time variable was dropped, due to the fact that it did not contribute meaningfully to explain the variance and it was causing errors in the running of the model.

Table 24 below provides the results from the HLM analysis for each of the three student learning outcomes. The results indicate that across all three models for the fixed effects, the only statistically significant contributor to the post-test scores are students' pre-test scores. For the Science Content Knowledge outcome model, the random effect of teacher accounts for 39.67% of the variance of the random effects, which is less than the residual variance. Similarly, for the Student Understanding of the Engineering Design Process outcome model, the random effect of teacher accounts for approximately 37.23% of the overall variance of the random effects. Lastly, the random effect of teacher accounts for only 1.90% of the random effects variance for the Perceptions of Engineering Design outcome model. Overall, the models suggest that only the pre-test scores provide meaningful contributions to the students' post-test scores. While the model

Table 24. Fixed and Random Effects for Three Student Learning Outcomes

Student Outcome	Science Content Knowledge		Student Understanding of Engineering Design Process		Perceptions of Engineering Design	
Fixed Effect	Estimate (*SE*)	*p*	Estimate (*SE*)	*p*	Estimate (*SE*)	*p*
Intercept	1.57 (.45)	.07	1.12 (.46)	.13	1.65 (.26)	.000*
Content Coverage						
C=2	-.47 (.60)	.52	-.10 (.61)	.88	.12 (.30)	.72
C=3	-.38 (.53)	.54	.20 (.53)	.74	.06 (.28)	.83
C=4	-.10 (.37)	.81	.20 (.38)	.64	.05 (.22)	.84
C=5	--	--	--	--	--	--
Quality						
Q=1	-.27 (.38)	.54	-.43 (.37)	.36	-.43 (.21)	.08
Q=2	.10 (.48)	.87	.01 (.48)	.99	-.14 (.22)	.58
Q=3	-.04 (.37)	.92	-.19 (.37)	.66	-.07 (.18)	.73
Q=4	--	--	--	--	--	--
Pre-test+	.33 (.39)	.000*	.34 (.04)	.000*	.63 (.04)	.000*
Random Effect	Estimate (*SE*)	*p*	Estimate (*SE*)	*p*	Estimate (*SE*)	*p*
Residual	.10 (.01)	.000*	.11 (.01)	.000*	.27 (.02)	.000*
Intercept	.06 (.07)	.33	.06 (.07)	.33	.01 (.01)	.66

Note. +Pre-test corresponds to the outcome test for each model.
**Significant at p<0.01*

Multiple Regression

Based on the constraints of the HLM model, and the small level 2 sample size, a multiple regression was run to determine if there were differences between groups of pre-service teachers. In order to group the pre-service teachers and their EDIS units into two roughly equal groups based on high OTL and low OTL environments, for each component of the OTL framework, pre-service teachers were ranked as "high" or "low" (see Table 25). Categorizations of high and low OTL environments are relative to the other units in the sample. High OTL environments are those with a higher degree of integration between the science and engineering design content, higher quality of the EDIS unit, and longer instructional time dedicated to the EDIS unit. For a full description of the grouping process see the data analysis section in Chapter 3 (see pages 77-79).

Table 25. Categorization of High OTL and Low OTL Environments

	Content Coverage		Quality		Time (min)		OTL	
Pre-Service Teacher	Initial Code	OTL Rank	Initial Code	OTL Rank	Initial Code	OTL Rank	Overall OTL Score	OTL Environment (Code)
Abigail	Balanced	2	3	2	270	2	6	High (1)
Beth	ED Focused	1	2	1	540	2	4	Low (0)
Marissa	Science Focused	1	1	1	90	1	3	Low (0)
Mark	Balanced	2	4	2	315	2	6	High (1)
Mary	Science Focused	1	4	2	315	2	5	High (1)
Robert	ED Focused	1	3	2	360	2	5	High (1)
Samantha	Indep. Science	1	1	1	90	1	3	Low (0)
Tess	ED Focused	1	3	2	90	1	4	Low (0)
Theresa	ED Focused	1	3	2	360	2	5	High (1)

Note. ED = Engineering Design; OTL = Opportunity to Learn

As shown in Table 25 above, five pre-service teachers' EDIS units were categorized as providing a high OTL environment, and four pre-service teachers' EDIS unit plans were categorized as having low OTL environments.

Science content knowledge. Regression analysis for the science content knowledge post-test outcome found that all three predictors (SCK pre-test, OTL category, and the interaction between SCK pre-test and OTL) were statistically significant (see Table 26). The results indicate that exposure to an EDIS unit in a high OTL environment can improve student post-test science content knowledge scores by 0.54 points on the 2-point

SCK scale. The full model accounts for approximately 18% of the variance in the SCK post-test scores.

Table 26. Multiple Regression Results for SCK

Variables	*B*	SE	Beta	*t*	*p*
Constant	0.95	0.09		11.26	.000
SCK Pre-test	0.49	0.06	0.75	8.98	.000
OTL	0.54	0.09	0.70	5.78	.000
SCK Pre-test*OTL	-0.44	0.07	-0.66	-6.43	.000

Note. Dependent variable = SCK Post-test score; OTL = Opportunity to Learn (0=low, 1=high); SCK = Science Content Knowledge

The regression equation for the model is given in Equation (1).

$$\textit{SCK Post-test} = 0.95 + 0.49(\textit{SCK Pre-test}) + 0.54(\textit{OTL}) - 0.44(\textit{SCK Pre-test*OTL}) \quad (1)$$

Plotting the equations derived from the multiple regression produces the graph shown in Figure 9, which displays predicted post-test SCK scores for both high and low OTL groups. From the graph, it is evident that the students in the high OTL environment are predicated to score similarly on the post-test (between 1.4-1.6) regardless on their initial pre-test score. This finding suggests that perhaps when given the highly structured environment accompanied by a high OTL unit plan, there is a ceiling effect on what students can score on the science content post-test. These results are encouraging for the students performing low on the pre-test because it suggests that exposure to the EDIS unit can result in post-test scores that are around the mean of the overall sample (μ=1.59). For those in the low OTL environment, the pre-test score strongly predicts a student's post-test scores. Stated another way, students performing low on the pre-test are likely to perform low on the post-test in the presence of a low OTL environment. And contrastingly, those scoring high on the pre-test are likely to score high on the post-test for science content knowledge. This finding suggests that those students who perform well on the pre-test are actually better in the less structured lower OTL environments.

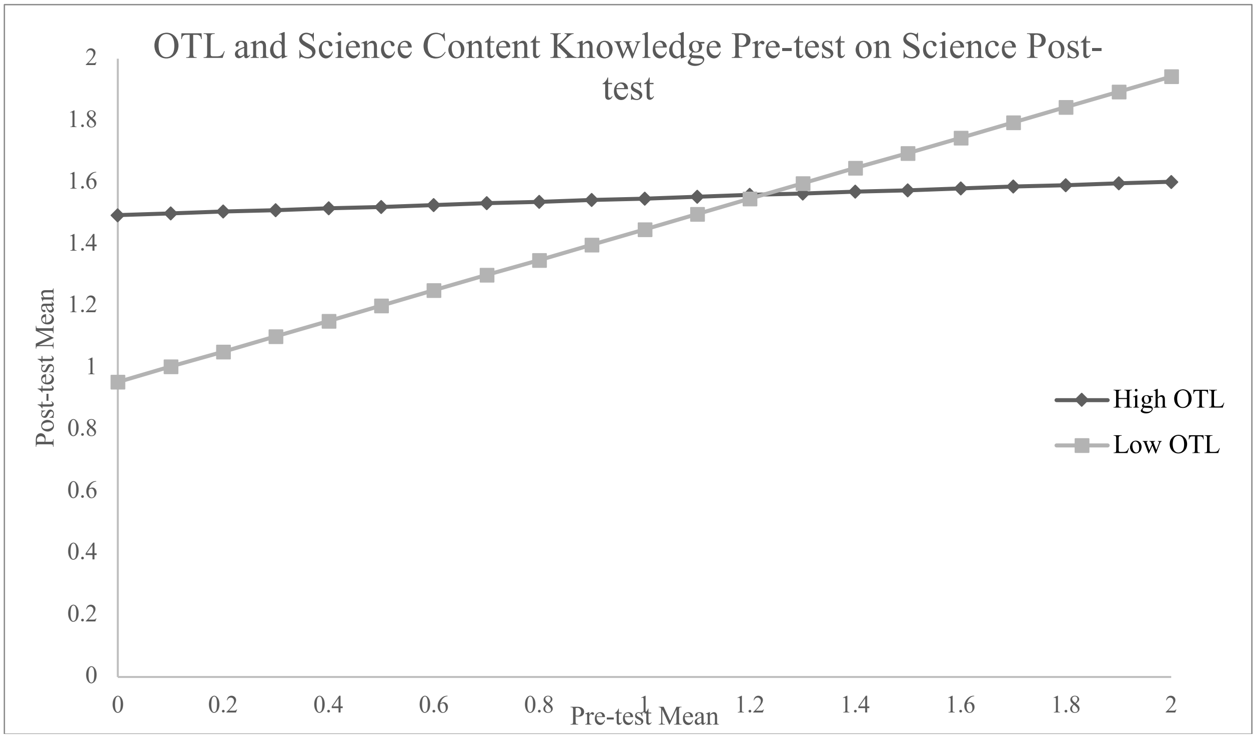

Figure 9. Predicated SCK Post-test as a Function of SCK Pre-test in High & Low OTL Groups

While Figure 9 shows the model of the predicted post-test science content knowledge scores for both OTL groups, it is crucial to note that the model extrapolates beyond the data sample. As such, when drawing conclusions from the model, it is important to look at the spread of the actual data. Figure 10 below shows a visual representation of the spread of the data points present in the high OTL environment group. This graph demonstrates that the data appears to be evenly spread across pre-test scores. This finding suggests that the conclusions mentioned above with regards to the regression model can still be drawn about this sample (i.e. high OTL environments can raise the post-test scores for those students with low pre-test scores). In reference to the low OTL environment (see Figure 11), it is evident that the preponderance of data points exists above pre-test scores of approximately 0.60 points. This finding suggests that while the conclusions mentioned above can still be drawn, it is important to note, that in the sample, students performing low on the pre-test lie above the 0.6 mark.

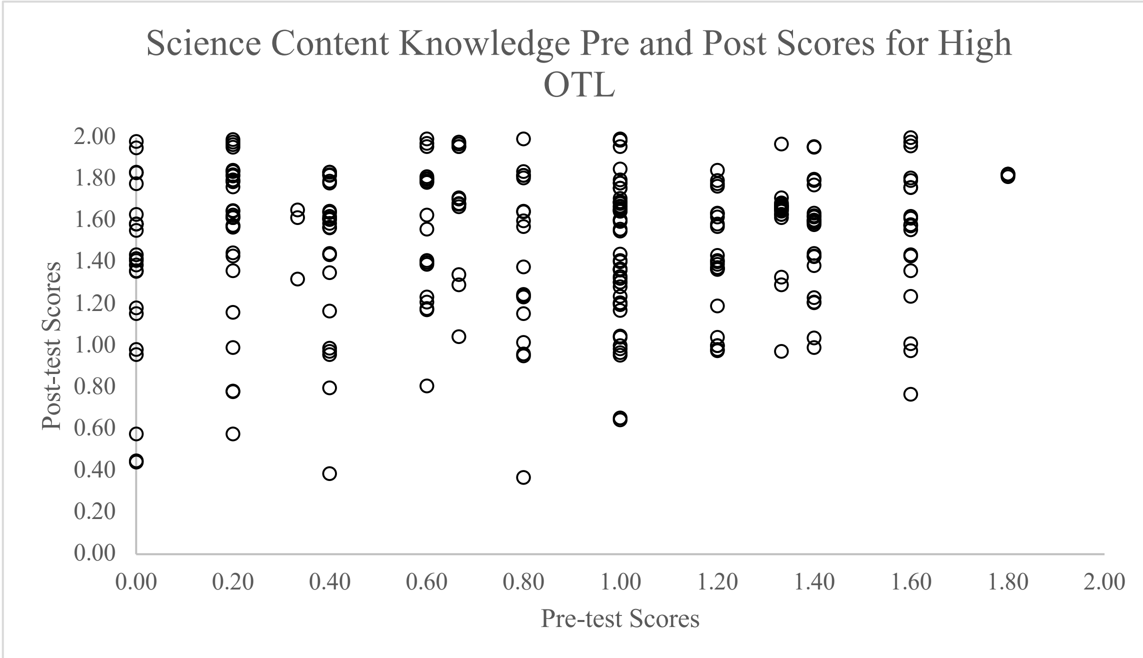

Figure 10. SCK (Pre and Post) Data Spread for High OTL Group
**Note*. Data points have been jittered to show a more complete picture of the spread.

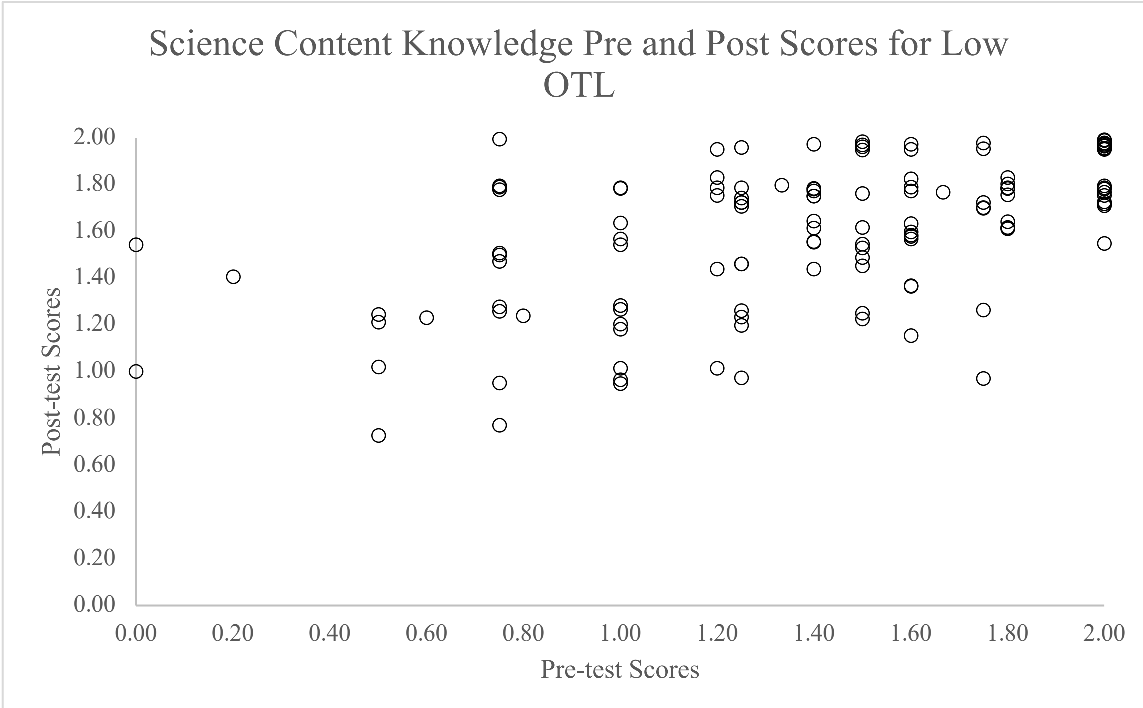

Figure 11. SCK (Pre and Post) Data Spread for Low OTL Group
**Note*. Data points have been jittered to show a more complete picture of the spread.

Overall, when comparing the performance of the students in the two learning environments, the pre-test science content knowledge scores were lower for those in the high OTL environment group (μ=0.84) as compared to the low OTL group (μ=1.46). The gap in the mean scores of the two groups is reduced following the EDIS instruction, with the high OTL group raising the student post-test mean (μ=1.54) to only slightly less than the low OTL group post-test mean (1.68). Figure 12 provides a visual of the reduction in the achievement gap between the two groups following exposure to the EDIS units. Findings suggest that although the students in the high OTL environment scored lower in the pre-test, this difference was greatly reduced by the EDIS units provided in the high OTL environment.

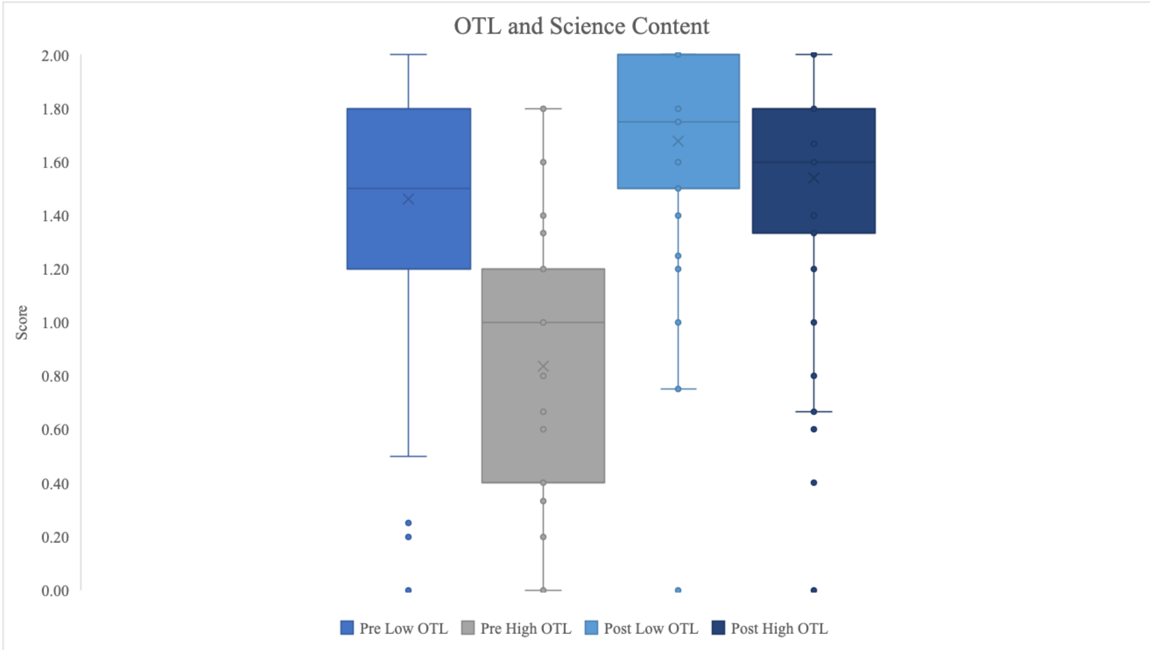

Figure 12. Boxplot of SCK Pre and Post-test Scores by OTL Group

Student understanding of the engineering design process. The regression analysis for the student understanding of engineering design process post-test outcome found that all three predictors were statistically significant (see Table 27). The results suggest that those in the high OTL group will score on average 0.68 points more than those not in the low OTL group. However, this gain is mitigated by the interaction term which is negative in this model. The full model accounts for 32.5% of the variance in the SUEDP post-test scores.

Table 27. Multiple Regression Results for SUEDP

Variables	*B*	SE	Beta	*t*	*p*
Constant	0.58	0.05		11.12	.000
SUEDP Pre-test	0.61	0.07	0.60	9.36	.000
OTL	0.68	0.06	0.75	10.76	.000
SUEDP Pre-test*OTL	-0.43	0.08	-0.44	-5.29	.000

Note. Dependent variable = SUEDP Post-test score; OTL = Opportunity to Learn (0=low, 1=high); SUEDP = Student Understanding of Engineering Design Process

The regression equation for the Student Understanding of Engineering Design Process outcome is provided in Equation (2).

$$SUEDP\ Post\text{-}test = 0.58 + 0.61(SUEDP\ Pre\text{-}test) + 0.68(OTL) - 0.43(SUEDP\ Pre\text{-}test{*}OTL) \quad (2)$$

A graphical representation of the multiple regression results is depicted in Figure 13. When predicting the SUEDP post-test mean score for individual students, those students receiving EDIS instruction in a high OTL environment are more predicted to score higher on the post-test than their peers in the low OTL group. Similar to the findings for the science content knowledge assessment, those students who appear to benefit more from the low OTL environment are those students who score highly on the pre-test. However, it should be noted that the difference between the scores for the two groups at the upper end of the scale is very small. Thus, the more robust finding is the difference in post-test scores amongst the two groups for those students scoring low on the pre-test. Additionally, the finding for the lower pre-test performing students is more impactful given the spread of the students in the current sample. In both Figures 14 and 15, it is evident that more of the data points lie at the lower end of the pre-test scores, suggesting that there are many students at this end from which the models were created.

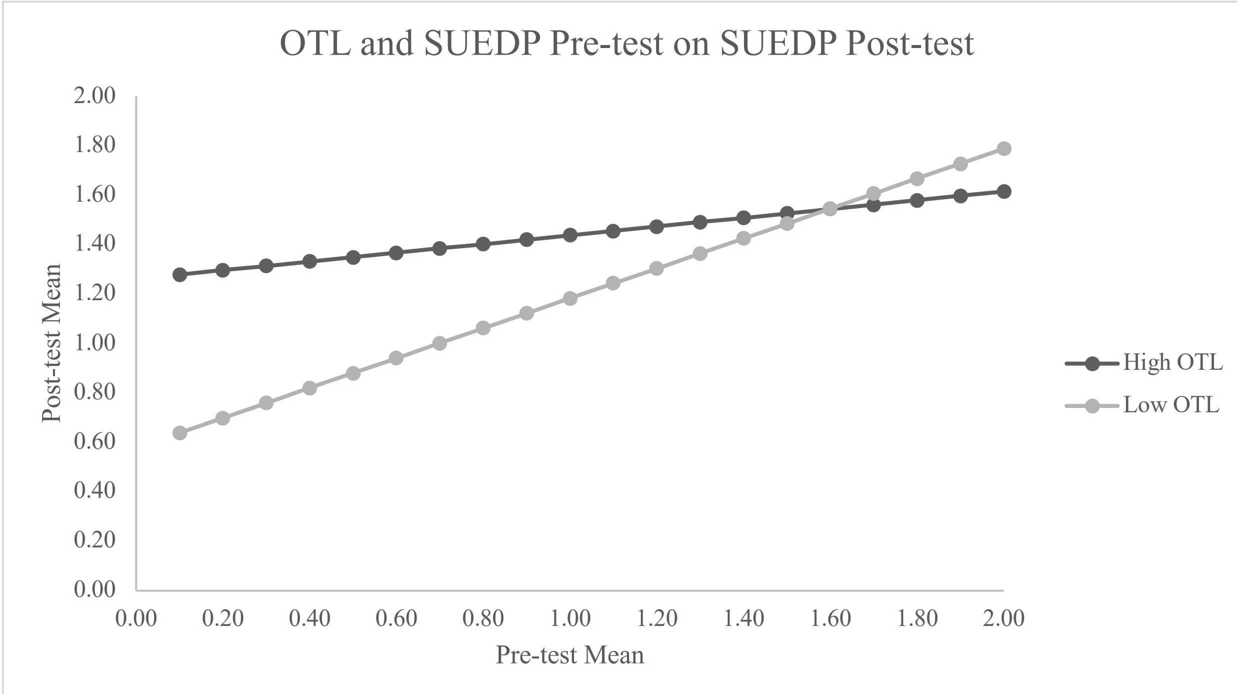

Figure 13. Predicted SUEDP Post-test as a Function of SUEDP Pre-test in High & Low OTL Groups

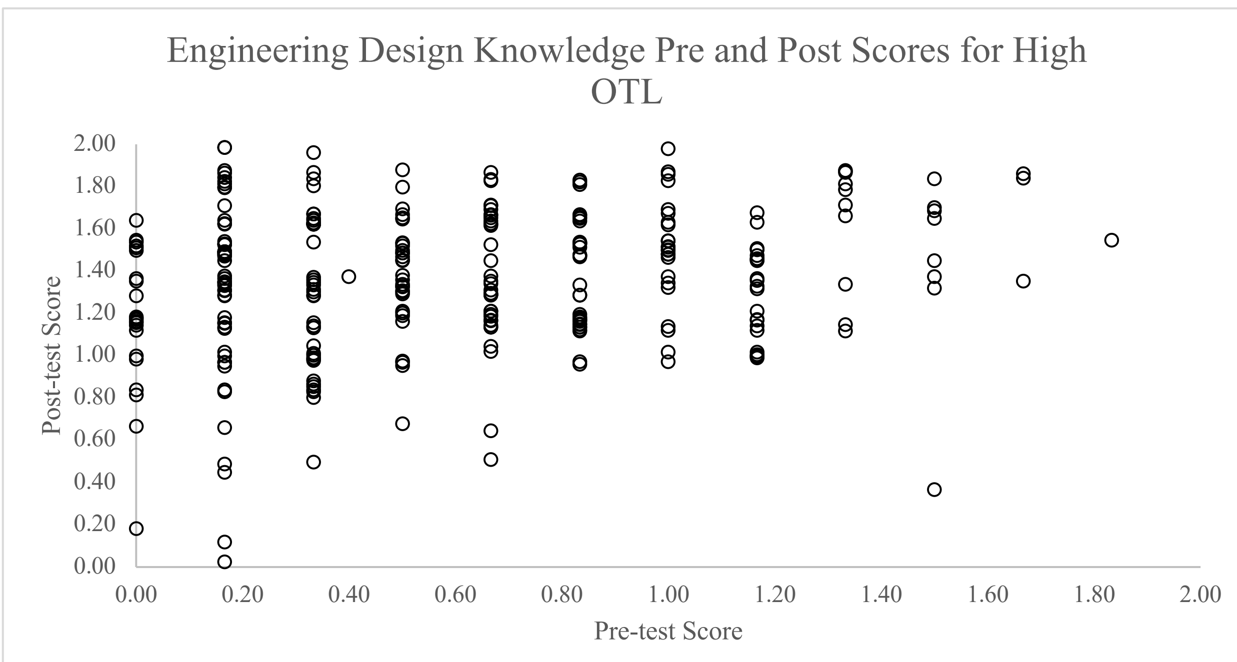

Figure 14. SUEDP (Pre and Post) Data Spread for High OTL Group
**Note*. Data points have been jittered to show a more complete picture of the spread.

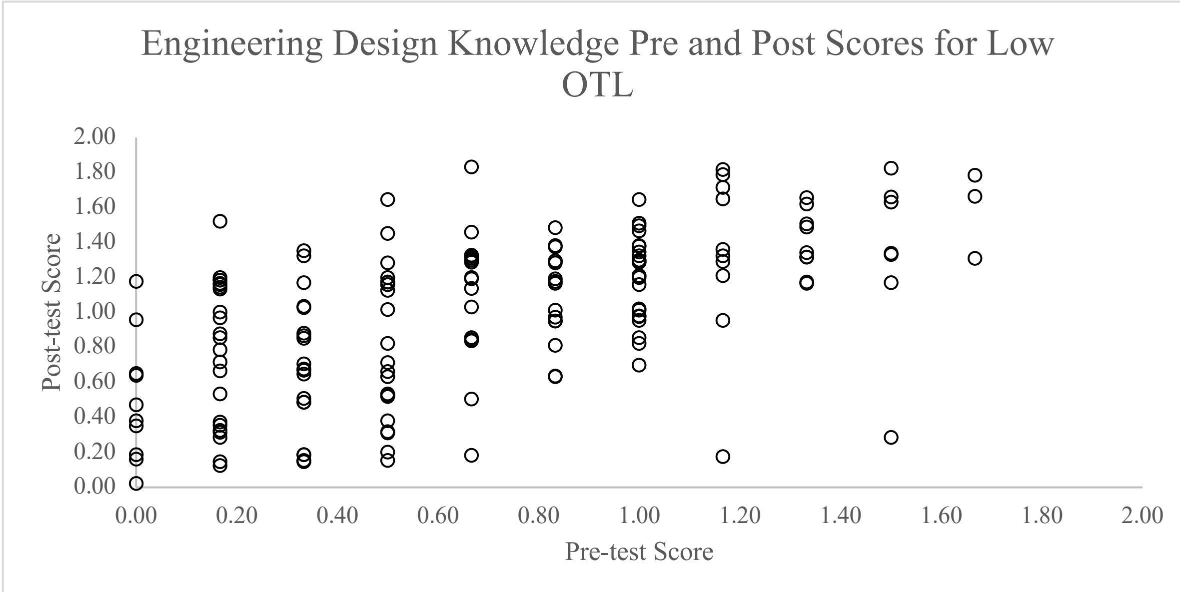

Figure 15. SUEDP (Pre and Post) Data Spread for Low OTL Group
**Note*. Data points have been jittered to show a more complete picture of the spread.

Overall, when comparing the performance of the students in the two learning environments, the pre-test SUEDP scores were very similar for both groups, with those in the high OTL environment group scoring slightly lower (μ=0.61) as compared to the low OTL group (μ=0.68) (see Figure 16). This suggests that both groups had an equal limited understanding of engineering design prior to EDIS instruction. However, following EDIS instruction, students who were exposed to the high OTL environment (μ=1.37) outperformed their peers in the low OTL environment group (μ=0.99). These findings suggest that while for both groups, exposure to EDIS instruction improved students' knowledge of the engineering design process, it was those students in the high OTL group, who received the greatest learning benefits.

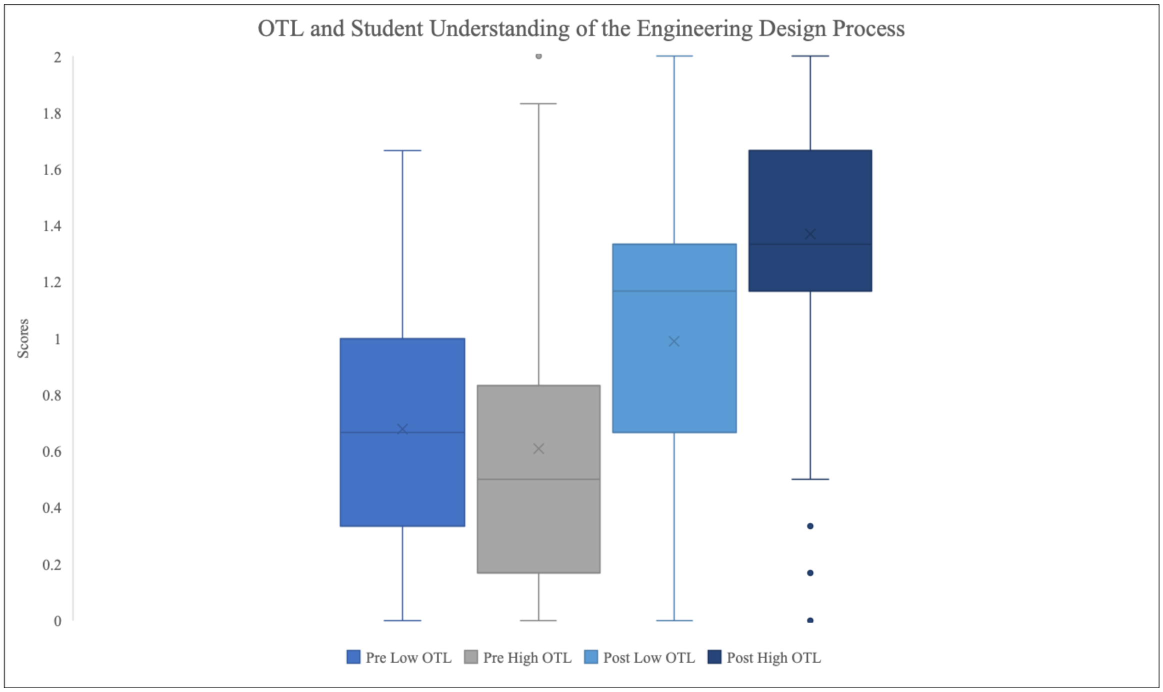

Figure 16. Boxplot of SUEDP Pre and Post-Test Scores by OTL Group

Perceptions of engineering design. The regression analysis for the perceptions of engineering design post-survey outcome found that all three predictors (PED pre-survey, OTL group, and the interaction between PED pre-survey and OTL) were statistically significant (see Table 28). Each point increase on the 5-point PED pre-survey corresponds to a 0.83 increase in the predicted post-survey score, and participating in an EDIS unit with a high OTL environment corresponds to a post-survey score increase of 1.03 points as compared to students in the low OTL environment group. The full model accounts for 46.4% of the variance in the PED post-survey scores.

Table 28. Multiple Regression Results for PED Survey

Variables	*B*	SE	Beta	*t*	*p*
Constant	0.91	0.19		4.91	.000
PED Pre-survey	0.82	0.06	0.81	13.97	.000
OTL	1.03	0.24	0.70	4.36	.000
PED Pre-survey*OTL	-0.26	0.07	-0.60	-3.55	.000

Note. Dependent variable = PED post-survey score; OTL = Opportunity to Learn (0=low, 1=high); PED = Perceptions of Engineering Design

The regression equation for the Perceptions of Engineering Design outcome is provided in Equation (3).

$$PED\ Post\text{-}survey = 0.91 + 0.82(PED\ Pre\text{-}survey) + 1.03(OTL) - 0.26(PED\ Pre\text{-}survey*OTL) \quad (3)$$

Although in Figure 17 below there appears to be differences between the models for low and high OTL with regards to predicting PED post-survey scores, most of the differences between the two groups occurs for predicting post-survey scores for students with pre-survey scores below 2.0 points. However, when looking at the spread of the data, there are very few students who fall below a pre-survey score of 2 points in either the high OTL (see Figure 18) or low OTL group (see Figure 19).

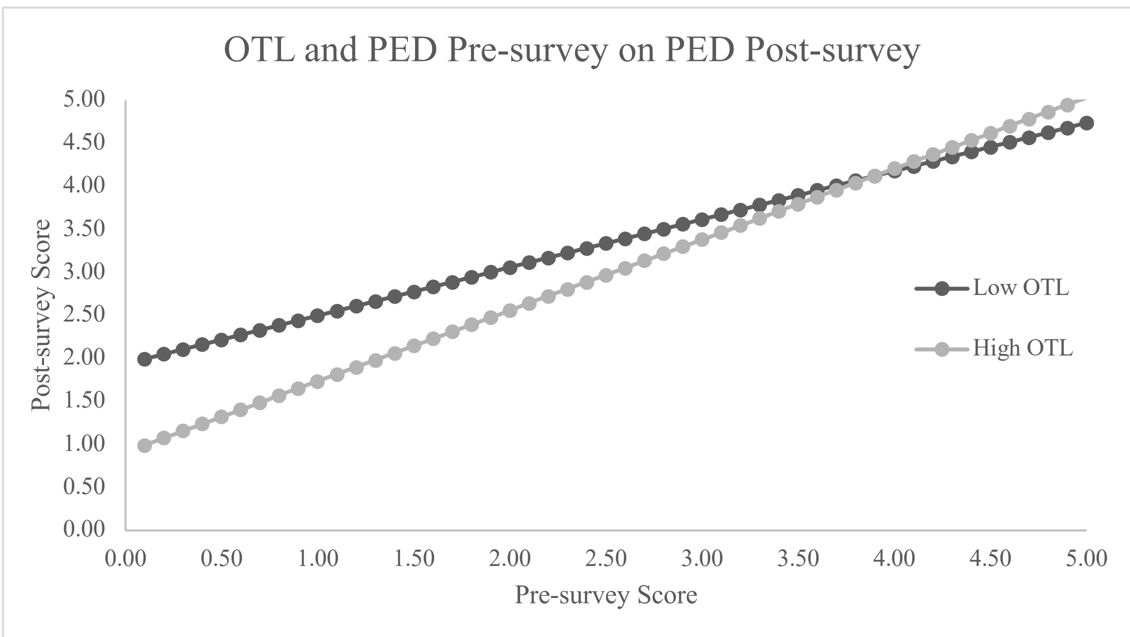

Figure 17. Predicted PED Post-survey as a Function of PED Pre-survey in High & Low OTL Groups

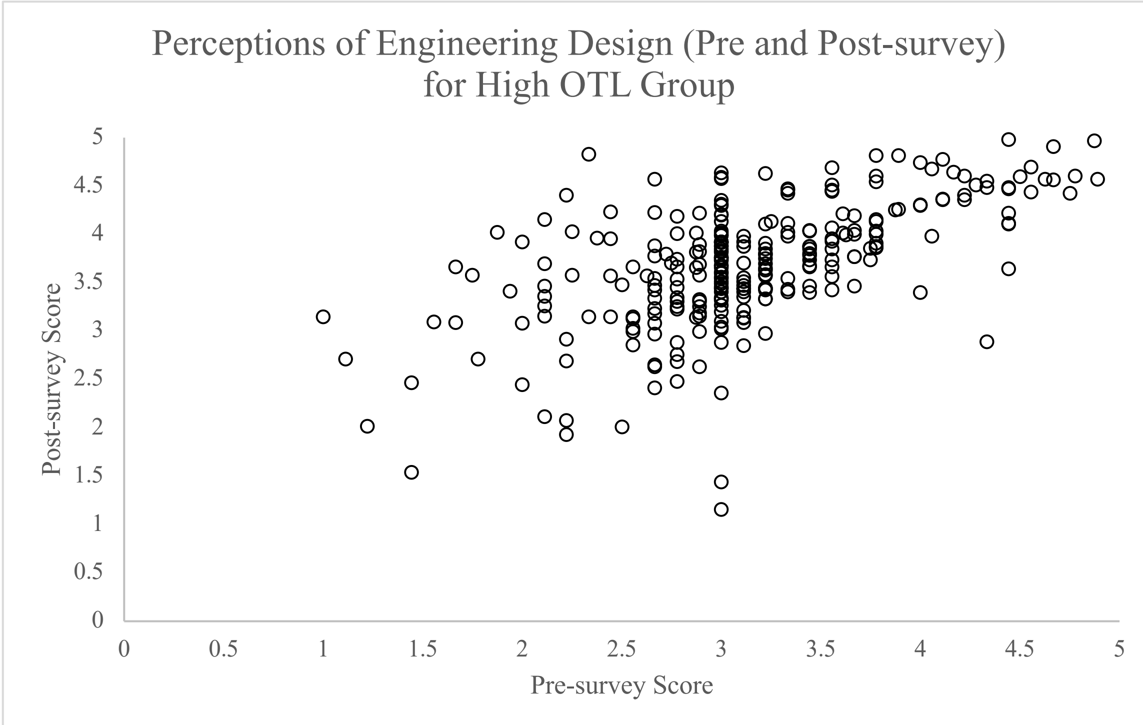

Figure 18. PED (Pre and Post) Data Spread for High OTL Group
**Note*. Data points have been jittered to show a more complete picture of the spread.

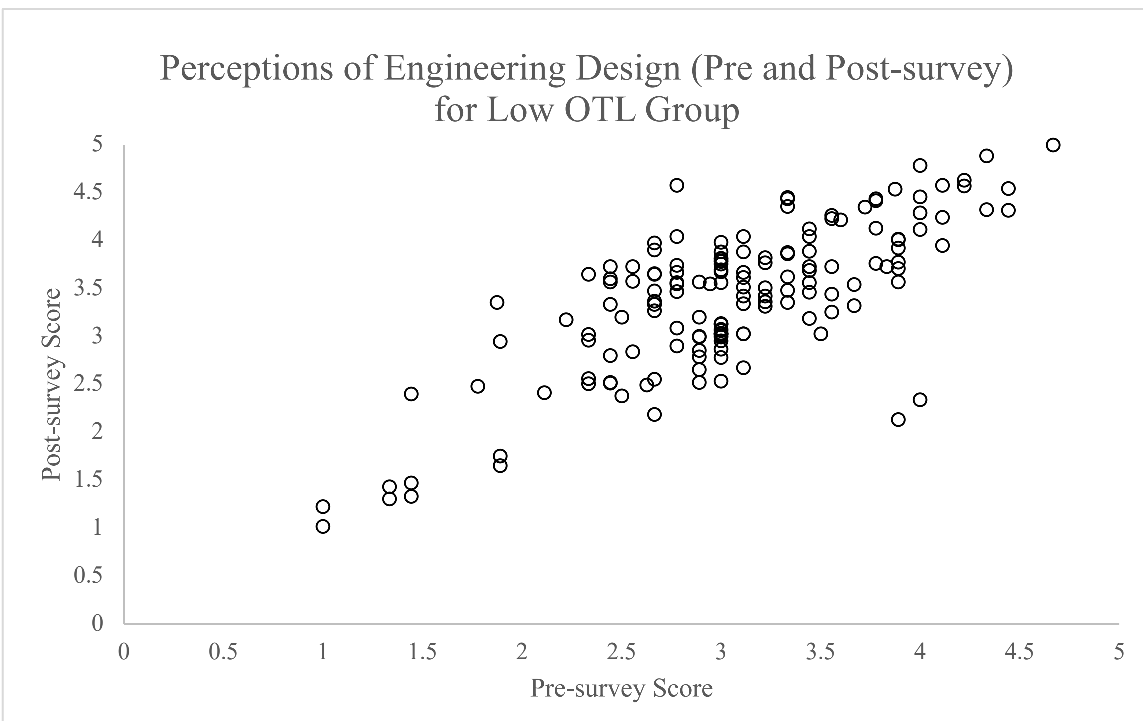

Figure 19. PED (Pre and Post) Data Spread for Low OTL Group
**Note*. Data points have been jittered to show a more complete picture of the spread

Therefore, the models do not appear to demonstrate differences when considering the spread of the sample data. Analysis of the data indicates that in the post-survey, both groups improved their perceptions of engineering design following the EDIS unit (low OTL = 0.37 point gain; high OTL = 0.56 point gain) (see Figure 20). This finding suggests that while both high and low OTL environments produce a gain in students' perceptions of engineering design, a high OTL environment may increase students' perceptions slightly more.

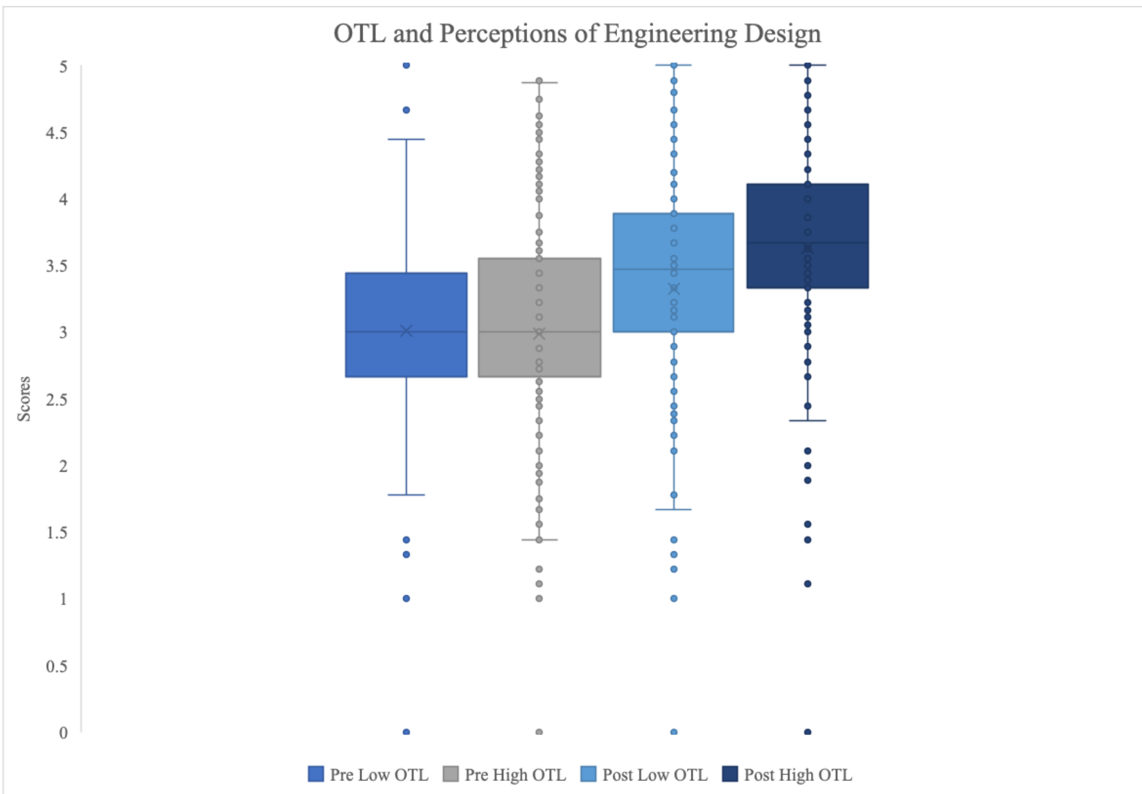

Figure 20. Boxplot of PED Pre and Post-survey Scores by OTL Group

Summary

Results of the hierarchical linear modeling indicated that pre-test scores were strong predictors of students' post-test scores. Limitations in the extent to which conclusions could be drawn from the hierarchical linear model resulted in the use of multiple regression. In order to determine whether or not there were differences in student learning gains between high and low Opportunity to Learn environments, pre-service teachers were categorized in to one of the two groups. Results and graphs from the multiple regression, show that there were differences between the two learning environments across all three outcomes – SCK, SUEDP, and PED. Of particular interest is the notion that high OTL environments appear to be particularly beneficial for students who perform low on the science content and engineering design content tests. While low-performing students still benefit from the high OTL environment in terms of increased perceptions of engineering design, the most impactful result is the amelioration of the content learning gap for low performing students as compared to their peers who performed high on the pre-tests.

In order to further understand what is occurring in high OTL environments with initially low-performing students, an exemplar classroom was selected for an in-depth qualitative analysis. Pre-service teacher, Mary, and her classroom was selected based on the following criteria: (1) students demonstrated statistically significant gains in both science and engineering design as measured by the three learning outcomes, (2) across pre-service teachers, this pre-service teachers' students had high post-test scores in both science and engineering design as measured by the three learning outcomes, (3) the pre-service teacher demonstrated a well-developed unit plan as defined by scoring highly on the OTL measures, and (4) the pre-service teacher had a large number of students. In the subsequent sections, Mary's class will be examined in greater detail to address the second research question.

Exemplar EDIS Unit in a High OTL Environment

The purpose of the exemplar is two-fold. First, it provides a rich and detailed account of both the student learning outcomes present in the individual classroom as well as what occurred during the instructional planning and implementation of the engineering design integrated science unit, and thus answering research question 2. This example was selected to explain what precisely occurred during the EDIS unit which led to the quantitative finding that in the presence of a high OTL environment, students with low pre-test scores can make significant learning gains in both science and engineering design and may in some cases ameliorate the gap between them and their peers who performed higher on the pre-tests.

Secondly, the exemplar allows for a more in-depth qualitative analysis of what the participants attributed the learning gains to in the EDIS instruction, which is in turn supported by observational data. Through this analysis, second research question is addressed. This section will provide the quantitative results from Mary's class to demonstrate that they are similar to the whole group results. The detailed account of the exemplar along with the qualitative analysis is the subject of Chapter 5.

Exemplar EDIS Context

The exemplar EDIS unit occurred in a biology classroom within a public high school located in small city in Virginia. The school operates on a block schedule consisting of 90-minute classes. Within this classroom, there is the mentor teacher, Mr. Jones, and Mary, one of the pre-service teachers enrolled in the science teacher education program at the local university, as described above. During the time of the study, in the fall of 2017, the mentor teacher and Mary had five biology classes (standard and honors sections) consisting of approximately 107 9th and 10th grade high school students, after removing students for missing data. Prior to teaching her engineering design integrated science unit, Mary developed her EDIS unit and then received feedback from both her mentor teacher and the science methods instructors (see Appendix G). The topic for Mary's engineering design integrated science unit was the cell membrane and cellular transport. The unit was adapted from the activity, *"Modeling a Membrane: Using Engineering Design to Simulate Cell Transport Processes"*, located in the practitioner journal, *The Science Teacher* (Mason & Evans, 2017). A more in-depth explanation of her unit plan is provided in Chapter 5.

Student Learning Outcomes in Exemplar EDIS Unit

Science content knowledge. Trends from the quantitative analysis of the overall sample are also present when examining the data from the case study pre-service teacher, Mary. As indicated in Table 19, Mary's students scored statistically significantly higher on the Science Content Knowledge post-test (μ = 1.61) as compared to the pre-test (μ = 0.42) (t_{106} = -27.76, $p<0.000$). When examining Mary's students' individual student scores on the Science Content Knowledge test (see Figure 21), the chart demonstrates the shift in students' average scores prior to and following the engineering design integrated science instruction. Prior to the EDIS instruction, almost half of the students scored between 0.2-0.4 points, on the 2-point scale in SCK test. Contrastingly, after learning about the cell membrane science content through the engineering design process, slightly more than half of these same students scored between 1.6-1.8 points on the post-assessment, which indicates that over the course of the EDIS unit, these students learned the targeted science content – properties of the cell membrane and cellular transport.

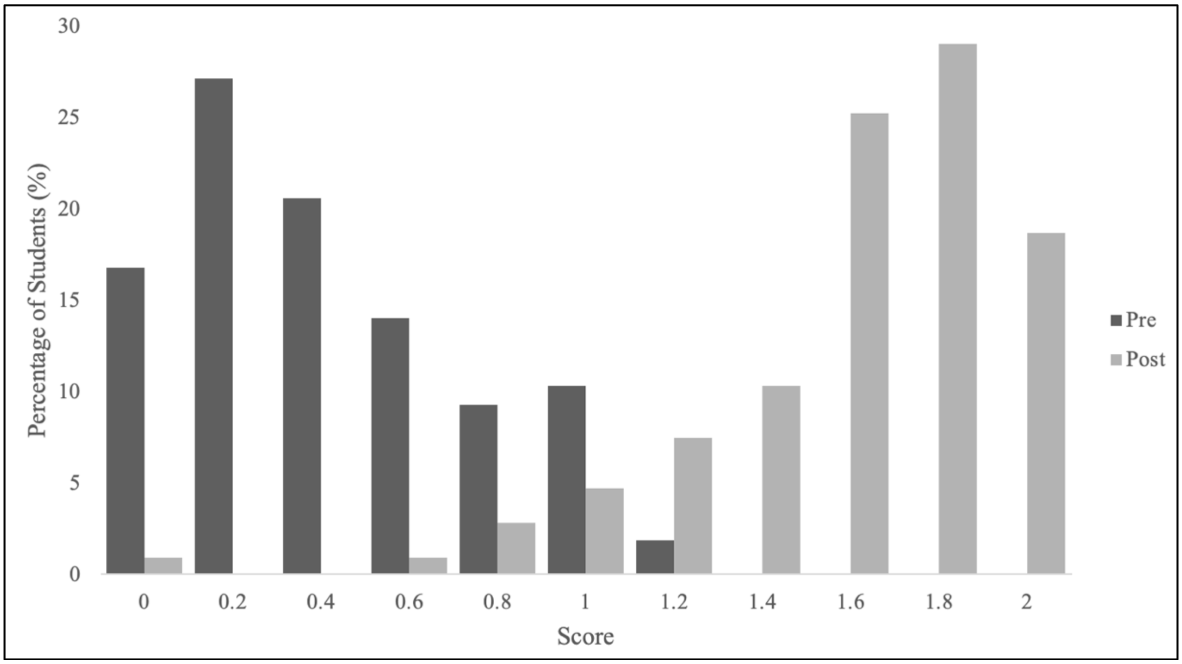

Figure 21. Pre and Post-test Average SCK for Mary's Students (percentage of students)

Furthermore, score for individual items on the SCK assessment (see Table 29) shows that over the course of the study, students improved in their ability to answer the following SCK questions regarding the cell membrane: (1) What is diffusion? (2) What type of molecules make 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 channel proteins and pumps that help to move certain materials from one side to the other. What are these channels and pumps made of? Of note, is students' understanding of SCK item 4, which pertains to the type of cellular transport that requires energy. Prior to the EDIS instruction, 70.4% of students received a score of 0. Many students left this question blank, wrote "I don't know", or provided the vague and incorrect answer of "all of the types". After the EDIS instruction in which students created their own cellular membranes and modeled various types of cell transport, 94.4% of the students answered the question correctly. This finding indicate that students learned specific science content knowledge taught during the EDIS unit.

Table 29. Percentage of Student Scores for Each SCK Item for Mary's Students

Science Content Knowledge Test Item	Score 0		Score 1		Score 2	
	Pre	Post (%)	Pre	Post (%)	Pre	Post (%)
1	30.8	4.7	68.2	61.7	.9	33.6
2	61.7	11.2	34.6	26.2	3.7	62.6
3	70.1	3.7	29.9	23.4	0	72.9
4	72.0	1.9	28.0	3.7	0	94.4
5	66.4	9.3	27.1	19.6	6.5	71.0

**Note* n=107; SCK = Science Content Knowledge

Student understanding of engineering design process. Similarly, Mary's students demonstrated statistically significant gains on the Student Understanding of Engineering Design Process post-test ($\mu = 1.49$) as compared to the pre-test ($\mu = 0.49$) ($t_{106} = -21.24$, $p<0.000$). An examination of the spread of the SUEDP pre and post-test scores, indicates a shift in greater understanding following exposure to the EDIS unit (see Figure 22). Prior to EDIS instruction approximately three fourths of the students scored at or below a score of 0.67 (2-point scale) on engineering design test. After learning about and engaging in the engineering design process, three fourths of the students scored above a 1.33, which is double the pre-test score of 0.67, which three fourths of the students fell below prior to instruction.

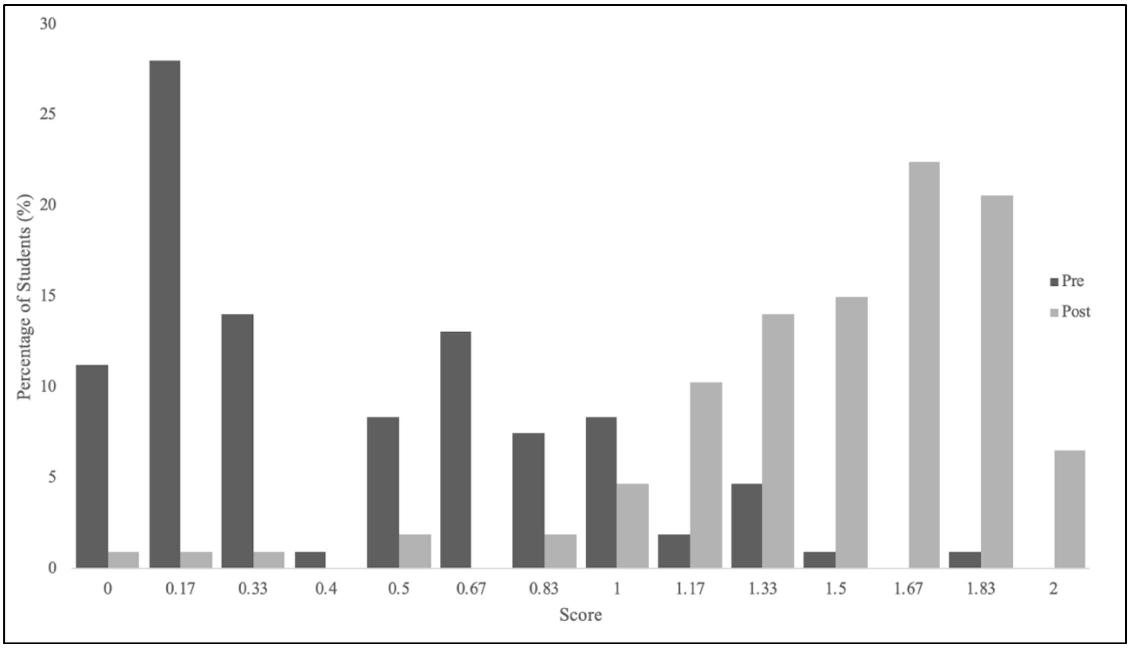

Figure 22. Pre and Post-test Average SUEDP for Mary's Students (percentage of students)

A table of the percentage of student scores for each item of the SUEDP test (see Table 30) shows a more nuanced depiction of the growth that occurred following the EDIS instruction. For example, only 9% of the students were able to provide a correct response when asked to describe the engineering design process, as compared to 67.3% after the engineering design integrated science unit. A change in SUEDP scores from pre to post-test suggests that through the intervention, students learned more about the engineering design process, its steps, and how it compares to the scientific method.

Table 30. Percentage of Student Scores for Each SUEDP Item for Mary's Students

SUEDP Knowledge Test Item	Score 0 Pre	0 Post (%)	1 Pre	1 Post (%)	2 Pre	2 Post (%)
1	22.4	3.7	72.0	39.3	5.6	57.0
2	75.7	9.3	15.0	23.4	9.3	67.3
3	52.3	7.5	34.6	7.5	13.1	85.0
4	80.4	5.6	15.0	57.0	4.7	37.4
5**	63.6	5.6	23.4	53.3	12.1	41.1
6	63.6	7.5	29.9	47.7	6.5	44.9

**Note* n=107; SUEDP = Student Understanding of Engineering Design Process
***Note* n=106; 1 missing value for pre-test

Perceptions of engineering design. Prior to the engineering design integrated science unit, Mary's students' average perceptions pre-test score ($\mu = 3.22$) was lower than their post-test score ($\mu = 3.72$) ($t_{97} = -9.16$, $p<0.000$) demonstrating statistically significant growth in student perceptions of engineering design following the unit.

Summary

When considering the whole sample, the dependent t-test results suggest that exposure to EDIS instruction can improve student learning outcomes in both science (as measured by science content knowledge) and engineering design (as measured by engineering design knowledge and perceptions of engineering design). Results from the multiple regression indicate that there are learning differences between the students, who were in a high OTL environment as compared to those students in a low OTL environment. Students who initially perform low on the pre-assessments greatly benefit from a high OTL environment as demonstrated by their large learning gains in their post-assessment scores.

Mary was selected, in part, because of the low pre-test scores that her students displayed and their subsequent learning gains following the EDIS unit. These results suggest that exposure to the *Creating Cell Membranes* EDIS unit, in the presence of a high OTL environment, resulted in a greater understanding of the science content, more knowledge of the engineering design process, and an increase in students' perceptions of engineering design. Overall, the results from Mary's students reflect the same trends in the overall data across all three sub-tests (i.e. exposure to EDIS instruction improved both science and engineering design student learning outcomes).

CHAPTER 5: QUALITATIVE RESULTS FROM EXEMPLAR EDIS UNIT

Results from the previous chapter indicate that Mary's students showed statistically significant improvement across all three measures of student learning – science content knowledge, engineering design knowledge, and perceptions of engineering design. Despite having some of the lowest pre-test scores, Mary's students had high post-test scores. Given these results and her EDIS unit providing a high OTL environment, her unit was selected for further examination. In this chapter, Mary's classroom is studied qualitatively to address research question #2: *To what extent does the qualitative data (unit plan, classroom observations, student responses & teacher interview response) from an exemplar of EDIS instruction, within a high Opportunity to Learn environment, help to explain the quantitative results of student learning outcomes?*

This research question is answered by providing an in-depth description of the instructional planning and implementation of the EDIS unit. Themes from student reflections and pre-service teacher interview responses are reported. These themes provide potential explanations for the student learning gains depicted in Chapter 4.

Instructional Planning & Implementation of Exemplar EDIS Unit

In an effort to address research question 2 and to provide a rich description of what a high OTL environment looked like in practice, the following section details the instructional planning, OTL alignment, and the way in which the unit was implemented.

Alignment of EDIS Unit with OTL Framework

As previously mentioned, in Chapter 3, each pre-service science teachers' EDIS unit plan and instructional materials were analyzed for each component of the OTL framework. In the sections below, Mary's instructional planning is examined through the results of the analysis of her unit plan (see Appendix G for Mary's full unit plan). Where appropriate, quotes from Mary's interview provide additional insight into her instructional planning. The topic for her engineering design integrated science unit was the cell membrane and cellular transport. The inspiration for Mary's unit plan came from a similar unit by "Modeling a Membrane" written by Mason & Evans (2017) published in the practitioner journal, *The Science Teacher*. Mary adapted the previously developed lesson plan to meet the needs of her biology classroom.

Content coverage. When assessing the content coverage of the unit plan, according to Kurz (2011) there must be alignment between the learning objectives and the assessed material. Because the assessed material included both engineering design and science content, the degree to which the unit integrated both content areas was the focus of the "content coverage" measure. After analyzing the unit plan, both raters categorized Mary's unit as a "science focused activity", which according to the *Continuum Model for Engineering Design and Science Integration* (Mumba et al., 2017), means that the unit "is designed to address mostly science core ideas and practices listed in the learning objectives, and engineering design is in support of the instruction". Thus, while both science and engineering design content exist and areas of the unit plan are balanced, preference was given to the science content. There are three justifications to support Mary's content coverage rating.

First, an examination of the essential questions, alignment to state and national standards, and learning objectives showed the incorporation of both content areas. For example, the unit addresses the following two essential questions: (1) how does the cell membrane help to maintain homeostasis inside of the cell and (2) what are the steps of the engineering design process? Similarly, both the science content and the engineering design content were aligned with the appropriate state and national standards (see Table 31).

Table 31. Creating a Cell Membrane Unit Alignment with State Standards and NGSS

	Standard	Specific connections to classroom activities
VA SOL	BIO.3 The student will investigate and understand the relationships between cell structure and function. Key concepts include d) the cell membrane model e) the impact of surface area to volume ratio on cell division, material transport, and other life processes	Students create models of the cell membrane to mimic the properties of a cell membrane.
	BIO.4 The student will investigate and understand life functions of Archaea, Bacteria, and Eukarya. Key concepts include a) maintenance of homeostasis d) human health issues	Students learn about homeostasis as they simulate cell transport. The design challenge is framed using real life human diseases
	BIO.1 The student will demonstrate an understanding of scientific reasoning, logic, and the nature of science by planning and conducting investigations in which f.) sources of error inherent in experimental design are identified and discussed.	Students follow the engineering design process to create and test their prototype.
NGSS	HS-LS1-2. Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms.	Students create models of the cell membrane in multicellular organisms.
	HS-ETS-1. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.	In the background information step, they identify specifications & constraints.
	HS-ETS-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.	Students design solutions to the design challenge by completing all of the steps in the engineering design process.
	HS-ETS-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.	Students evaluate their prototypes through testing and compare them to other prototypes.

Note: VA SOL= Virginia Standard of Learning; NGSS = Next Generation Science Standards

However, the unit shows that Mary listed more science content than engineering design learning objectives. Below is a complete list of the learning objectives (See Figure 23). Because the learning objectives are the actual information and skills that the teacher hopes that the students take away from the unit, the preference towards more science content and practices results in the rating of the unit having a greater science focus as opposed to a completely balanced unit.

Students will know:

(a) The fluid mosaic model of a membrane emphasizes the arrangement and function of a bilayer of phospholipids, transport proteins, and cholesterol;
(b) 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;
(c) Diffusion occurs in cells when substances (oxygen, carbon dioxide, salts, sugars, and amino acids) that are dissolved in water move from an area of higher concentration to an area of lower concentration;
(d) 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;
(e) 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);
(f) Active transport refers to the movement of solid or liquid particles into and out of a cell with an input of energy;
(g) Genetic predisposition towards diseases impacts human health. Awareness of genetic predisposition allows individuals to make lifestyle changes that can enhance quality of life.
(h) Engineering design is an iterative process

Students will understand:

(a) There are multiple forms of transport across a cell's membrane that help to maintain homeostasis;
(b) The engineering design process.

Students will do:

(a) Explain engineering design process
(b) Apply the engineering design process.
(c) Identify the different parts of a phospholipid bilayer.
(d) Define and provide examples of osmosis, diffusion, and active transport.
(e) Model a semi-permeable membrane.
(f) Differentiate between passive and active transport, including examples of each.
(g) Design and build a semi-functional model of the phospholipid bilayer.
(h) Model how a concentration gradient influences the transport of materials across a membrane.

Figure 23. Creating a Cell Membrane EDIS Unit Learning Objectives
**Note.* Engineering design objectives are bolded for contrast.

The following sequence of events should be noted. Initially, Mary taught both the steps of the engineering design process and then the science content via an interactive presentation. This was then followed by the actual engineering design challenge, in which students applied their knowledge of the cell membrane, as they engaged with the steps of the engineering design process, to design a solution to the challenge

The second justification for Mary's content coverage rating was that after formally learning about the EDP and science content, the EDP was used solely as a means for understanding the science content. For example, after initially learning about the EDP, student interactions with the engineering design process were in pursuit of creating a scientific model to help explain scientific content (i.e. cell membrane and cellular transport). This is evident in the design challenge during which students were tasked with "acting as biomedical engineers who are responsible for designing a cell membrane that allows different substrates to cross it via a variety of transport channels and proteins to replace the faulty membranes in cystic fibrosis patients" (see Figure 26). Thus, while students needed to understand and use the engineering design process to solve the scientific problem, the focus of the unit was on the science content.

Third, the categorization of Mary's unit plan as "Science Focused" is further supported by her interview responses. When asked how well she thought that the engineering design process was incorporated into the science content, she said "*I felt like I pre-taught science concepts, and I reinforced it with the engineering. I don't know how I would have done it [if]as they were engineering, they were learning the [science] content for the first time"* (Mary, Interview, 11.29.17). This statement suggests that the science content was initially taught and then through the engineering design process, the science content was revisited. This indicates that while both content areas were present, there was more of a focus on the science content over the engineering design content.

Quality. Like the other unit plans, the quality of Mary's EDIS unit plan was assessed based on the Curriculum Quality Rubric (Guzey et al., 2016a). For the overall rating of the effectiveness of the curriculum unit, Mary's unit received the highest rating of a 4 out of 4. According to Guzey et al. (2016a), the overall score is reflective of "the effectiveness of the curriculum unit in having students learn the knowledge and skills and/or practices identified in [the] national and state education standards." Mary demonstrated the effectiveness of her unit plan through a rich description of what she anticipated occurring during each day of her engineering design integrated science unit. Throughout her unit plan, Mary detailed the instructional sequence that occurred, the teacher's role, and expected student actions for each segment of her unit. The description of her "lesson segments" allowed for the reader to see how the learning objectives and standards would be addressed through instruction.

For example, at the beginning of Day #2 in her EDIS unit (see Appendix G), Mary stated that students would complete a formative assessment reviewing cellular transport. She listed the question on the assessment and explained that she will go over the answers with students while they review their own work. It is clear that through this assignment, students would address VA SOL BIO.3e, along with several of the science content learning objectives (i.e. *Students will know 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 and without the use of energy*). Another example of Mary demonstrating how her learning objectives and standards would be met through instruction, was her Engineering Design Overview Table provided in her unit plan, which showed how all of the components of the EDP were integrated into the overall unit (See Table 32).

Table 32. Creating a Cell Membrane Engineering Design Overview

Design Process	Guiding Principles	Project Description
Problem Definition	- Students should identify users and needs. - Challenge should be relevant to students' lives - Students define specifications & constraints	• Students will design a model of a cell membrane to help them further understand the components of the membrane and 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 disorders such a cystic fibrosis • They will need to pitch their prototype to the "board of a hospital"
Develop Knowledge	-Student-centered approach to background concepts	• Students will investigate the parts of the cell membrane (hydrophobic tails, hydrophilic heads, proteins and cholesterol) and cell transport.
Generate Multiple Ideas	- Guide students to develop multiple solutions with rationales	• Students will sketch designs individually and collaboratively and plan out what materials they want to use • Students will be prompted to justify the final solution
Develop Prototype	- Explore different ideas through multiple representations	• Students will create a sketch and outline their budget as a group for the materials they want • They will be allowed to re-evaluate their material usage if they'd like throughout the process.
Test and Evaluate Prototype	-Create tests to learn how prototypes behave -Solicit feedback about design	• Students will present their prototypes and describe each of the required parts and the types of transport they are involved in. • They will test the functionality of their prototype by massing the materials before and after travelling through the membrane.
Revise Prototype	-Guide students to use feedback to revise -Reflect and give justifications	• Students will discuss how they could revise designs based on their test results, feedback, and observations of their classmates' designs. They won't actually carry out this phase but will reflect in writing.
Reflection and Extension	- Support reflection - Check how well solution meets project criteria -Guide students to apply content in new context	• Students will be reflecting on the entire EDP 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.

**Note. Abbreviated from the version provided in Mary's Lesson Plan (see Appendix G)*

This overview allowed the readers to clearly see where the students interacted with the following standards: VA SOL BIO.1f; NGSS HS-LS1-2; NGSS HS-ETS-1,2, &3 and some of the learning objectives (e.g. Students will apply the engineering design process). In addition to her demonstration of the way in which students were to engage with the content in order to attain the learning objectives, Mary's high scores on the sub-components of the Quality measure also contributed to her high overall score. For instance, Mary received the highest scores (4=excellent) on the following categories: motivating and engaging context; engineering design challenge; integration of science content; performance and formative assessment; and organization. Overall, Mary demonstrated attention to detail when planning for her engineering design integrated science unit and conveyed what students would do in order to meet the learning objectives and the national and state standards.

Instructional Time. For the final component of the OTL framework, students were exposed to the Creating a Cell Membrane EDIS unit for approximately 360 minutes. The unit spanned four class session of 90 minutes each. Overall, there were five sections of biology for a total of 124 high school students.

Description of Implementation

While observations of the EDIS unit depict a strong adherence to the EDIS unit as it was planned, there were some minor yet obvious differences during the implementation. Most notably was Mary's review of the cellular transport processes before students were engaged in building prototypes. During a break between class periods on the second day of instruction, Mary expressed some concern about her explanation of cellular transport during the first day of instruction. She and the researcher discussed what was most essential to teach students and what higher level concepts should be eliminated from the review. The researcher also shared with her a cellular transport review sheet that she had used with her students when she taught high school biology. She then incorporated this worksheet into her review with all of her classes (see Day 3). Observations of her adherence to and minor deviations from her EDIS unit plan was further supported through Mary's interview. When asked to what extent the lesson proceeded as planned, she stated,

> "*The engineering design process part matched up well. It was the content that I had to reiterate and teach and reteach, because I didn't like the way that I did it the first time…The engineering design process that the kids went through, it was pretty much as I planned it. I think that I was confusing in my initial explanation of [the science content], and I wanted to break it down and help them categorize it a little bit better*" (Mary, Interview, 11.29.17).

As such, it cannot be assumed that the well detailed unit plan provided by Mary is the same instruction that students received. Therefore, I will present the thick rich description, which is often included in similar analysis such as a case study (Yin, 2017). The description will depict the four-day enactment of Mary's unit plan in her classroom. This account is based on the field notes collected while observing her classroom. Because Mary taught the unit in all five biology classes, the descriptions for what occurred during each day are a compilation from all five class periods. Due to the practical limitations of working within schools, issues such as the lunch schedule, field trips, and athletic events, resulted in not all of the classes completing the exact same tasks on each day. However, the description provided below speaks to the sequence of instruction that was presented to all students.

Day 1. On the first day of the unit, students were told that they would be working on an engineering design project for the next few days. The students appeared to be very enthusiastic at this announcement. Students were then placed into four groups, in which they were tasked with brainstorming all of the jobs that engineers could have. One group discussed how engineers fail a lot. Mary took this moment to reinforce the notion that failure can be a good thing. Many of the ideas shared amongst students were types of engineers, such as electrical, aerospace, biochemical, and computer engineers. Other suggestions included responsibilities of engineers, such as designing things, doing math and science, planning, formulating ideas, and creating (see Figure 24).

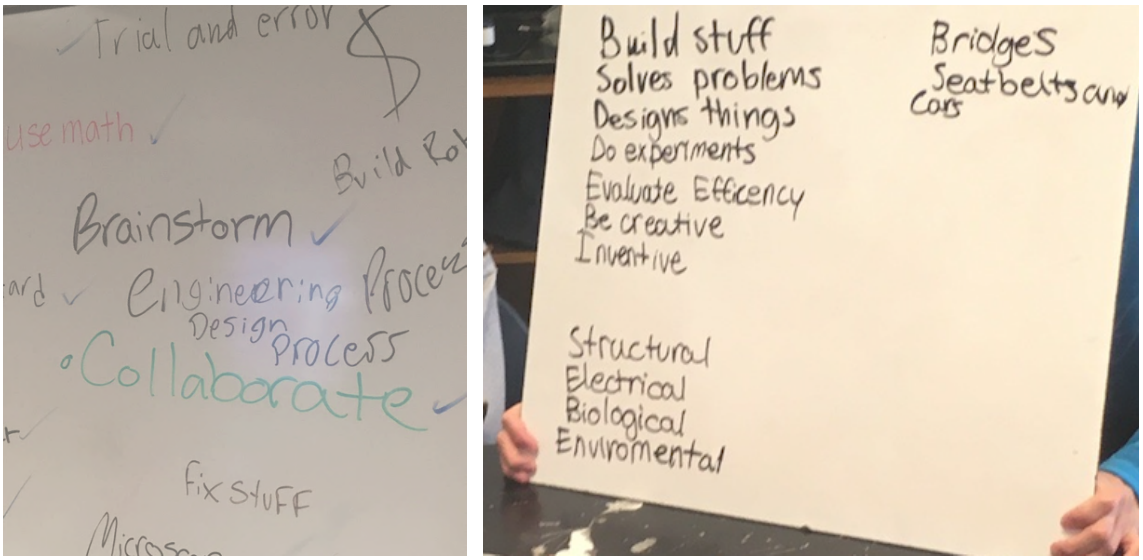

Figure 24. Day 1- Samples from Student Brainstorming Session on the Tasks of Engineers

Mary transitioned into a discussion of the engineering design challenge by stating that the students will act as biomedical engineers when creating their cell membranes. Next, Mary began her interactive PowerPoint presentation, which included a description of engineering design and an overview of the engineering design process (see Figure 25).

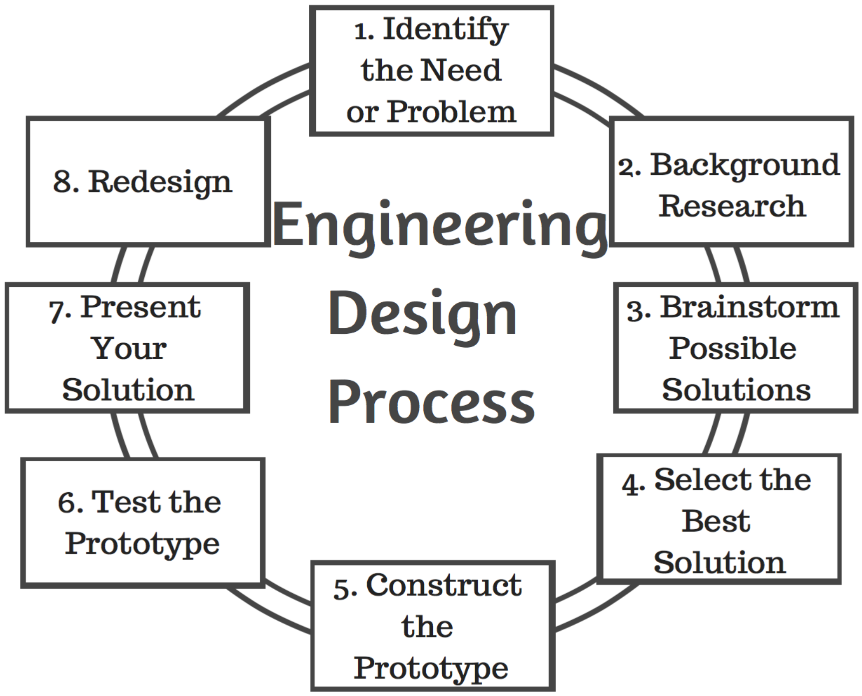

Figure 25. Engineering Design Process Model

While presenting this model of the engineering design process to the students, Mary specifically noted the iterative nature of the process. She asked students to define the term iterative. Students responded by saying "repetitive" and "infinite". Then, as Mary described each step of the engineering design process, she also explained what students would be doing during each step. For example, during step 1: "Identify the need or problem", Mary provided students with a condensed version of their engineering design problem/challenge: *Design and build a functional, three-dimensional model for cell transport. The model needs to accurately mimic the structure and function of the phospholipid bilayer of the cell membrane and allow different substrates to cross the membrane by various forms of cell transport.* Specifically, she highlighted the purpose of the engineering design portfolio and how they were to document their work. She also stressed the collaborative nature of engineering.

Next as a small group activity, students brainstormed the ways in which the engineering design process and the scientific method are similar and different. During this time, students were allowed to use their computers and electronic devices to obtain the answers. This brief activity concluded with Mary reviewing the differences between the two processes on the board. Lastly, students learned about genetic diseases which are a result of malfunctioning cell membranes, such as cystic fibrosis and Muscular Dystrophy.

Day 2. The agenda for the second day of the unit was listed on the board (1) cell membrane and cell transport notes (2) engineering design introduction steps (1-4). The class began with a description of the cell membrane via a PowerPoint presentation. Students were shown various renderings of the cell membrane to highlight the components of the cell membrane along with its "fluid mosaic" like nature. Students were then directed to the proteins that reside within the cell membrane – channel, carrier, cell recognition, enzymatic, and receptor proteins. Next, Mary introduced the types of cellular transport, simple diffusion, facilitated diffusion, osmosis, active transport, along with types of solutions. At times, it appeared as though students were confused, particularly when Mary was drawing sample diagrams of osmosis on the board. One of the hypothesized reasons for student confusion was that the explanation she provided was in terms of the water molecules, but her drawing depicted the solutes, such as salt. However, at this point in the lesson, the term "solute" had not been defined for the students. This confusion resulted in a conversation between the researcher and Mary during which the researcher provided her with a review worksheet of cellular transport. All of this occurred largely through direct instruction with the assistance of various visual aids, PowerPoint slides, video clips, illustrations. Students took notes and engaged in whole class discussions when prompted.

One exception to the direct instruction format occurred while Mary was discussing the types of solutions. She presented students with a demonstration of an egg which had been soaking overnight in distilled water. The egg was much larger than its initial size, due to osmosis. She then told the students that she would next put the egg into a hypertonic solution so that they can observe it shrink in size. The students appeared to be very excited about the egg, and in several classes, students continuously bring up the topic of the egg throughout the class period. At this point, students were then told that they were done with notes and were to begin a discussion on the ED scenario (see Figure 26).

Engineering Design Scenario:

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.

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 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."

Figure 26. Creating a Cell Membrane Design Challenge (Abbreviated)

After learning of the ED scenario, students were instructed to move to one of the lab tables in the back of the classroom, which was designated as the "materials table". Students were then able to observe all of the potential materials that they had access to when building their model. They were also told that each material had a specific cost associated with it to simulate a "real-world" scenario. Materials included: Styrofoam balls, scotch tape, duct tape, cotton balls, toothpicks, drinking straws, coffee stirrers, rubber bands, paper clips, craft foam, yarn, cheese cloth, pipe cleaners, aluminum foil, Play-doh, and Q-tips (See Figure 27). Students are told that their designs will be tested to see how certain molecules move through them. Mary told them that sand would represent oxygen and carbon dioxide molecules, glucose is represented by a small "pom-pom" fluff ball, and the marbles are the large substrates that must move via active transport.

Figure 27. Materials Table for Creating a Cell Membrane EDIS Unit

Back at their seats, students transitioned into step two of the EDP, background research, and they were told to use their notes to sketch passive and active transport. The purpose of this step was to ensure that students have the background science content knowledge of cell membranes and osmosis to move on to EDP step 3: brainstorming multiple solutions. As students individually brainstormed their designs by drawing diagrams in their design journals, Mary walked around the classroom assisting students. Throughout this process, the majority of the students appeared to be on-task and excited. I overheard several students talking about their designs, including one student who said, "*I feel pretty confident about my design*." Student questions were often very thoughtful and indicated that they had been paying attention when learning about the cell membrane. For example, one student asks, "*Are we building an entire membrane or just a section?*" Next, the students were put into groups, in which they shared their individual designs and then created an overall group solution to fulfill step 4 of the EDP: Select the best solution. Several students demonstrated engagement in the unit by inquiring about bringing in materials from home, to which Mary agreed.

Day 3. At the start of third day of the EDIS, students were provided with a chance to review the relevant science content information, as a class through review worksheets and diagrams. The review worksheet was provided by myself to Mary after we had a conversation about student confusion surrounding cellular transport. Additionally, Mary explained the concepts of concentration gradients and equilibrium.

Next, the students moved into their groups and began to work on engineering design step 5: constructing the prototype. Many of the groups used straws, Q-tips, craft foam, tape, and Play-doh as their primary building materials. Throughout the class period, Mary continuously monitored the progress of each group and answered questions. She occasionally provided clarification on the design challenge or helped students to think through the design process. Figure 28 depicts some of the prototypes that the students designed.

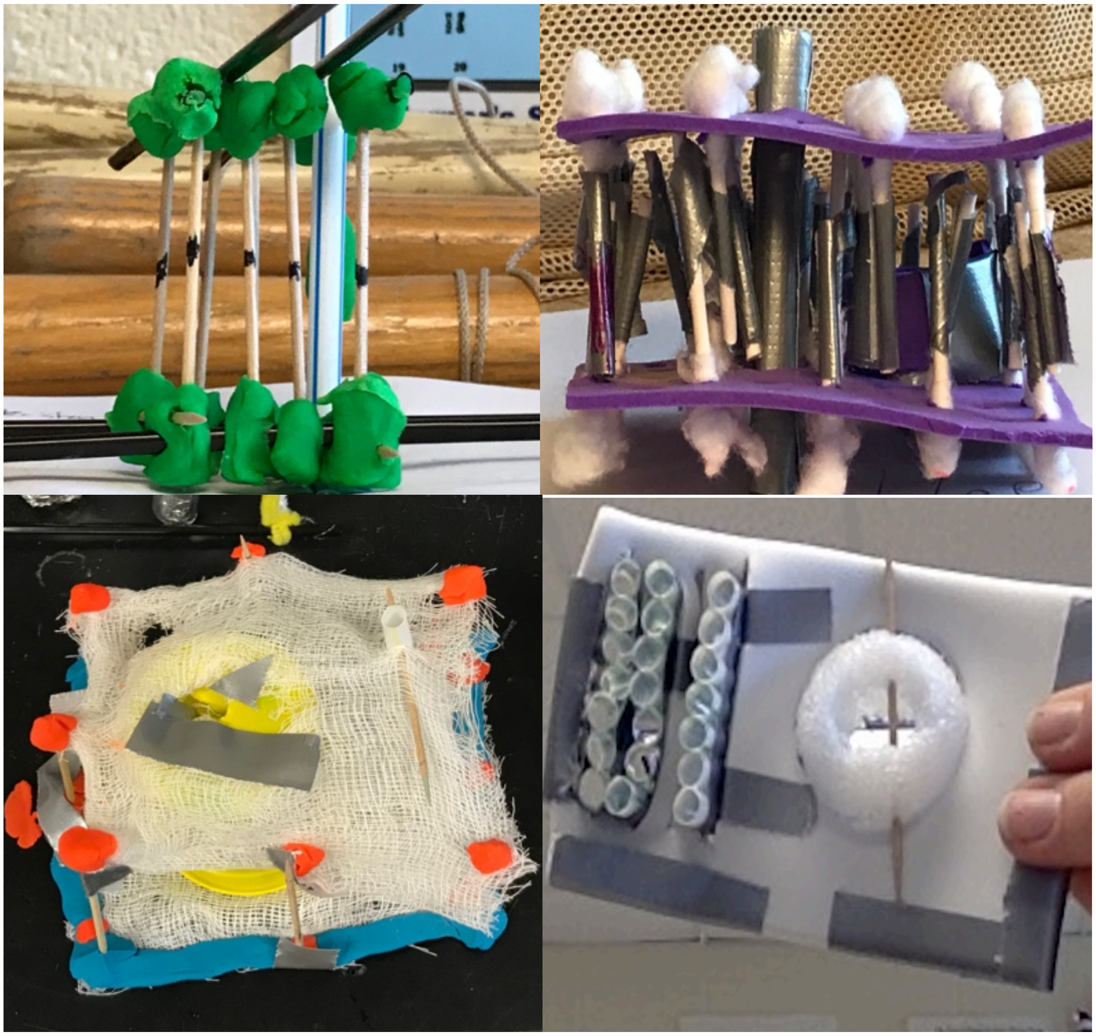

Figure 28. Examples of Students' Cell Membrane Prototypes

During the class period, students moved to the materials table and "purchased" materials from the shopkeeper, the mentor teacher, using their material slips to keep track of their expenses. Students in several classes became very invested in spending the least amount of their budget in pursuit of bonus points. Thus, students began to negotiate and bargain with the mentor teacher for supplies. He attempted to implement some real-world principles into his negotiations by only providing students a fraction of their money back when they made returns to account for a "restocking fee". In another interaction, the mentor teacher told one group that they needed to plan better before buying supplies after complaining to him that they don't have enough money. Students appeared engaged in their work and most of the conversations are on-topic. Some students were concerned that they would not have time to complete their design and appeared upset to have to pack up, at which point, Mary told the students that they can come back and work outside of class time. This indicated a high degree of dedication to the project by both the students and the teacher.

Day 4. The agenda for the fourth day consisted of finishing up building the prototypes, sharing the designs, discussing the redesign step of the engineering design process, and completing their design packets. While the students concluded their prototype construction, the mentor teacher and Mary circulated around the room to assist groups of students. During the construction phase, students were encouraged to "test" their own prototype to see if certain materials, the sand, water, pom-poms, and marbles, could pass through the cell membrane and simulate various types of transport (see Figure 29). The ability to informally test their prototypes prior to presenting to the teacher, resulted in students making modifications or redesigning components of their prototype throughout the construction phase. For example, one student told his group, "We are going to have problems with our channel proteins". To which a group member student replied, "We can test it before! Let's get a cup of water."

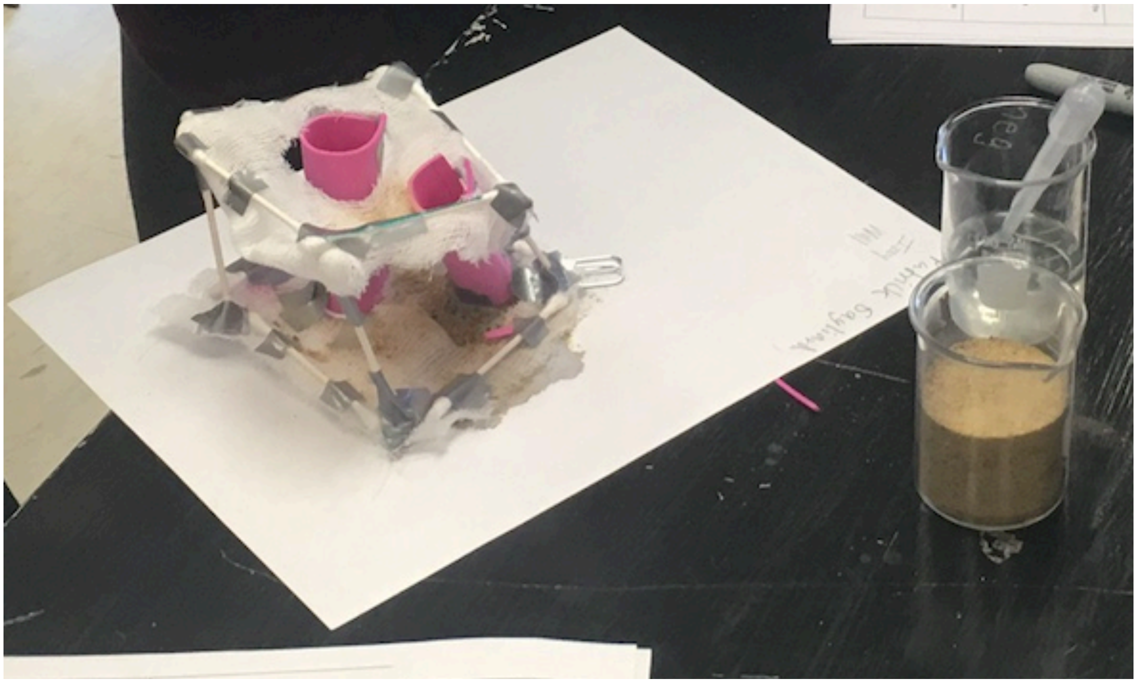

Figure 29. An Image of a Prototype About to Undergo Testing

At the conclusion of the construction phase, students were told that they were to perform a “gallery walk”, in which they were to circulate around the room and observe other groups’ designs. Following the gallery walk, students were instructed to begin “formally testing” of their prototype. This was accomplished by explaining to Mary the various components of their design, their alignment to the actual structures of a cell membrane, and actually testing the membrane for various types of transport using the sand, water, pom-poms, and marbles as molecules. Students were then graded based on their explanations of their prototypes. Many groups took this phase of the engineering design process seriously by practicing their presentations, engaging in discussions as to who should present each section, and some even wrote down a presentation script.

To conclude the unit, the students were told to complete their design packets and turn them in for a grade during the following class period. Within their packets, they were asked to use their test results and observations of other groups’ prototypes to draw a redesign of their prototype. Due to time constraints, they did not actually re-build their redesigned prototype. During the following class period, they took the post-assessment, comprised of the SCK, SUEDP, and PED instruments.

Summary of Instructional Planning and Implementation

As a whole, Mary's EDIS unit was categorized as providing a high OTL environment. Although there was a greater focus on the science content, her unit demonstrated content coverage of both science and engineering design. The unit was of high quality in its alignment of the instructional practices with the standards and learning objectives, and the unit was taught over four days. Overall, the enacted unit was very similar to the planned EDIS unit. As noted in the observations as well as Mary's interview, changes were made to her presentation of the specific science content of cellular transport. She both made her own adjustments and was provided additional support in reviewing the science content. Throughout the unit, particularly during the engineering design process, students were engaged and interested in the design challenge.

Participants' Views on Their Experiences with the EDIS Unit

After providing a thick description of the instructional planning and implementation of the exemplar EDIS unit, I will now turn to the themes that emerged from the qualitative analysis of student responses to the open-ended questions and Mary's interview, supported by evidence from classroom observations. The purpose of these themes is to address the third and final research question: "*To what extent does the qualitative data (unit plan, classroom observations, student responses, & teacher interview responses) from an exemplar EDIS instruction, within a high Opportunity to Learn environment, help to explain the quantitative results of student learning outcomes*?" As previously stated, Mary's students had some of the lowest pre-test scores for their understanding of both science and engineering design content. However, after engaging with the EDIS unit in the high OTL environment, her students not only demonstrated statistically significant learning gains, but had the highest post-test scores for their understanding of the engineering design process and their perceptions of engineering design. As such, it is important for their voices to be heard and to understand their experiences and what they attribute their learning gains to.

Science & Engineering Design Content Knowledge

In reflecting on their experience, students were asked to explain how they thought that the engineering design process helped them learn more about the cell membrane and cellular transport. Overall, there were 107 student responses with only three students who rejected the premise of the statement, that they learned the science content through engineering design, which suggests that a majority of the students recognized their learning through the EDIS unit.

Through the analysis of student responses on whether the engineering design processed helped them learn more about the cell membrane, two main themes emerged: (1) visualization of the process and (2) hands-on building and creating of the cell membrane prototype. These themes are presented below and excerpts have been used to explicate them.

Visualization of the process. Approximately, 49% of students attributed their learning of the content covered in the unit to the ability to visualize the cell membrane and to see what the microscopic process of cellular transport looks like. For example, one student said,

> “*The engineering design processed helped me to learn more about the cell membrane because it gave me a visual representation of what each object does. When we were learning about the cell membrane it really didn’t make any sense to me. But being able to actually model it out helped me a lot*.” (Caleb).

Caleb’s response is emblematic of what many students said about the importance of having a visual representation of not only the cell membrane, but also a functioning model that depicts the various forms of cellular transport. In addition, Caleb also specifically stated that this method of learning was more beneficial to him as compared to other methods of instruction (i.e. the direct instruction that preceded the use of the EDP). While this sentiment was only echoed by five total students, it is powerful because students made the distinction between instructional practices on their own and felt strongly enough to articulate it in response to the open-ended question.

Another student, Patricia, provided an explanation for why the visual of the cell membrane is helpful for learning, stating, “*It gives me an awesome visual to remember.*” The memorable nature of the models is perhaps one justification for why students attributed their learning of the scientific content to the visualization of the concept. The purpose of the model and its power to help students remember content is the fact that parts of their own model are representations of actual microscopic cell membrane. The value of using the model as an analogy to real components and processes within a cell was evident in the classroom observations. For instance, while students were building their prototypes, Mary would circulate around the room and assist groups. In one particular situation, Mary asked the group to explain all of the different components of their model. She then probes them to explain there the outside and inside of the cell would be in relation to their model. She then explains to the students that what they are creating is just a section of the cell membrane and that in real life the cell membrane would continue (Class 4, Observation Notes, 11.9.17).

The role that the visual models played in student learning was emphasized by Mary during her interview. When asked about how the engineering design helped the students better learn the science content, Mary's response focused on the visual that it provided students.

> "*I think it helped them conceptualize the fluid mosaic model of the cell membrane, because in a 2D picture it's kind of hard to see, especially when you're just looking at a snapshot of the cell membrane….I think having them draw it out and actually move physical molecules or models of molecules through their membrane designs, it helped them to conceptualize the 3D model better…obviously, they can't see it in real life.*" (Mary, Interview, 11.29.17)

It is imperative to note that in her response, Mary not only highlights the importance of the visual model, but includes the importance of students actually building and creating their own models, which is the focus of the next theme.

Hands-on building and creating. About a third of students attributed their learning to the physical building and creating of the cell membrane prototypes. Many of the responses discussed how the actual creation of a prototype provided them with a deeper understanding of how the processes worked because they were able to physically manipulate the model. A subset of those respondents (10% of participants) specifically discussed how the building of the prototypes was helpful for facilitating learning because it required them to understand the science content, in order to create a successful prototype. One of the students, Maria, articulated this sentiment in her response,

> "*The engineering design process helped me learn about the membrane since it made it necessary to understand what all of the different parts of the cell membrane are. It also helped by giving a physical example of the membrane. Building/engineering things makes me learn things more thoroughly since it is necessary for the challenge*" (Maria).

As such, in order for students to be successful with the engineering design challenge, they first had to understand what cellular transport was and how substrates move across the cellular membrane and then transfer that knowledge to build a prototype. The concept of knowing the scientific material prior to designing the engineering solution was expressed by Mary at the beginning of the EDIS unit. On the first day of the EDIS unit, Mary introduced students to the career of biomedical engineering and then told the students that they will be biomedical engineers during the engineering design challenge. In one her classes Mary specifically asked the students, "*Why would engineers need to know scientific knowledge before doing engineering?*" To which one student responded, "*It is more efficient that trial and error*." Mary then transitioned into discussing the diseases which are impacted by imperfect cell membranes and explained that students were going to be addressing these issues in the design challenge (Class 6, Observation Notes, 10.30.17). It is this direct application of the science content that Mary considers to be the greatest benefit of incorporating engineering design into science classrooms.

> "*I think it gives students a new modality of interacting with the content, rather than a worksheet or even just a project. It has them actually creating something. And I think treating obviously on Bloom's taxonomy is the highest level. So that helps reinforce [and] solidify the concepts better that are sometimes more like fact recall in science.*" (Mary, Interview, 11.29.17)

Overall, when asked to explain components of the EDIS unit that contributed to an increase in student content knowledge, participants often cited the creation of the prototype step both for the visual representation that it provided, as well as an avenue for students to apply their scientific knowledge to solving the engineering design challenge. Now we will turn our attention to what students enjoyed about the engineering design process and thus may have contributed to the statistically significant increase in students' perceptions of engineering design. It is important to note that while the acquiring of content knowledge and perceptions of engineering design are in separate sections here, they are often conflated. As one student wrote, "*It gave me something to visualize as a cell. Also, it was a fun project, and when things are fun they stick in my mind better*" (Veronica).

Perceptions of Engineering Design

In the PED survey students were asked to rate their perceptions about engineering design through statements like the following: "I like engineering", "I like using engineering design to learn science", "Engineering challenges are fun", and "I would rather do engineering than regular science". It then follows that examining student responses to the question "What did you like most about the engineering design process?" might provide insight into students experience with the engineering design during the EDIS unit and therefore, shed light on the statistically significant increase in students' perceptions of engineering design present following their engagement in the EDIS unit. Out of the 107 students, only one student said that they didn't like anything about the EDP. Therefore, 99% of the students who responded were able to identify at least one thing that they enjoyed about the engineering design process. The following are the three main themes that emerged regarding what students enjoyed about the EDP: (1) designing and building the cell membrane prototype; (2) redesigning and improving the prototype; and (3) brainstorming. These themes will be explored in greater detail along with additional supporting evidence provided by Mary's interview and classroom observations.

Designing and building the cell membrane prototype. It should come as no surprise, that the top student response (approximately 41% of respondents) was the designing and building of the cell membrane prototype. An additional 7% of students stated that they enjoyed the hands-on nature of the EDP, which likely refers to the "constructing the prototype" step in the engineering design process. Examples of common student responses to the question were "*I liked the designing part of engineering design*" (Rachel) and "*I like how the engineering design process enabled you to create/build things because I like hands-on learning*" (Christina).

Several students specifically stated that they enjoyed the hands-on approach to learning as compared to other methods of learning. One student wrote, "*I liked that we got to build something instead of just writing stuff down on a piece of paper*" (Robin). Throughout the classroom observations, it was noted several times during the direct instruction portion of the EDIS unit that students did not respond to the Mary's questions when asked. The direct instruction occurred largely at the beginning of the unit when Mary was first introducing the EDP and the science content. While there may be several reasons for student non-response when asked questions, it appeared as though students were less engaged or did not remember the science content (Class 4, Observation Notes, 11.3.17). However, it is important to note that students were not complete disengaged during the direct instruction. It was often observed that students were actively taking notes and were not on their phones or computers during the direct instruction, so it is difficult to ascertain the level of student engagement during this time as compared to the hands-on portion of the unit (Class 7, Observation Notes, 10.31.17).

However, student enjoyment was evident throughout the "creating the prototype" phase. Through this phase of the EDIS unit, it is noted several times in the field notes that "*students appear engaged in the activity. Almost all of the students are talking about the project and engineering design. There are very few conversations that are off-task.*" (Classes 1 and 7, Observation Notes, 11.2.17; Class 6, 11.3.17). Several student groups were also engaged in the competitive cost aspect of the design challenge. In one particular class, there was a strong focus on obtaining the lowest overall budget for their design. Many of the groups in this class period "spent" under $10 on their prototypes and students were often negotiating prices with the mentor teacher, who ran the supplies table (Class 7, Observation Notes, 11.2.17).

Additionally, students' investment in their prototypes was apparent when they were told that it was nearing the end of the class period and that they had to finish up the construction of the prototype. In one particular class period, students were visibly upset that they had to pack up, and Mary offered for the students to stay after school to continue working on their prototypes if they didn't have a bus to catch. She also suggests that they work on their prototypes during lunch (Class 7, Observation Notes, 11.2.17). On the whole, students were enthusiastic about the construction and design portion of the EDIS unit.

Redesigning and improving the prototype. The second theme, which emerged from the student responses data was that students enjoyed the redesigning phase of the EDP. Although this process required them to complete more work and to redo something that they already did, approximately 21% of the students stated that they enjoyed the redesign phase of the EDP the most. To justify their selection of redesign as their favorite part of the EDP, many respondents cited that they enjoyed learning from their mistakes and that they appreciated having multiple opportunities to get to the solution. The following are several student responses when asked what their favorite part of the EDP was.

> "*That it never really ends. There are constant changes and improvements you can make based off of the knowledge you learned from the previous trials*" (Isabella).
>
> "*If the design was bad, then you can fix that and not just leave it as a failed project*" (Alexander).
>
> "*I liked getting to actually build the final product, putting all of my skills to use in one area. I also like that it is okay to make mistakes the first couple of tries because you can just learn from it, make changes and move on without it affecting you*" (Rebecca).

Rebecca was also one of 6% of students who in the other reflection survey question, attributed her learning of the scientific content in part to the redesign component of the EDP. "*It helped me because I was able to fully immerse myself into the material and put the facts to use through planning, designing, building and revising"* (Rebecca). Thus, students not only understood the iterative and cyclical nature of the engineering design process, but they actually enjoyed learning from their mistakes and attempting different solutions, and several students went further in stating that the redesign was what helped them to learn the scientific content.

There was one "formal" redesign phase at the end of the EDIS unit, in which students documented in their design portfolios what they would hypothetically do differently if given the time to completely redesign. However, it was observed that students engaged in a more "informal" redesign process throughout the construction of their prototypes. Mary explicitly encouraged students to practice testing their prototypes prior to formally presenting them and testing them in front of her (Class 6, Observation Notes, 11.9.17). This provides students with the opportunity to revise any apparent flaws in their prototype before formal testing, and thus reinforces the concept that it is okay to learn from failure. Mary intentionally stressed the value of learning from mistakes when she first introduced the concept of engineering and engineering design at the beginning of the EDIS unit. When asking the students to think about types of engineers, one student said that engineers fail a lot. Mary then took time to talk with the group about how failure can be a good thing. Overall students enjoyed the opportunity to learn from their mistakes and to continually improve upon past designs.

Brainstorming and student creativity. In addition to constructing and redesigning prototypes, the third most enjoyed aspect of the EDIS unit was the brainstorming phase and/or the opportunity for students to express their creativity and autonomy (approximately 17%). Some students expressed an affinity for the individual brainstorming step "*I liked the brainstorming part by ourselves, since often I run out of time to come up with ideas before my partners do*" (Emma), and yet others enjoyed the collaborative brainstorming component, "*I liked how many people in the group could contribute ideas into one solution*" (George). As such, the individual and collaborative components of the brainstorming process allowed this step to appeal to various types of students.

Throughout the individual brainstorming phase, students were observed as they quietly sat at their lab tables working on their design portfolios. Some of the students were researching images of diffusion and cellular transport on the internet, while they drew their pictures. During this time, Mary walked around and provided individual assistance to confused students (Class 4, Observation Notes, 11.1.17). The benefit of the collaborative brainstorming was observed in a brief exchange between two students. Students just finished gathering into their assigned groups when one student asked, "Do you have an idea? Because I don't." One of her group members responded, "I feel pretty confident about my design" (Class 1, Observation Notes, 10.31.17).

During the brainstorming phase, students were able to demonstrate their creativity and student choice through the designs that they sketched and the materials that they selected. The idea of student choice was captured in Fred's response, "*I liked that we were able to choose which materials we could use in our project*". Student creativity and choice were evident during observations of the brainstorming and designing phase. One of the groups was discussing the possibility of using coffee stirrers and cheesecloth for their prototype. To convey her idea of layering the materials, one of the girls in the group said, "Think about this like making a layered lasagna" (Class 7, Observation Notes, 11.2.17). The creativity of the designs is apparent in the variation amongst the prototypes (see Figure 30).

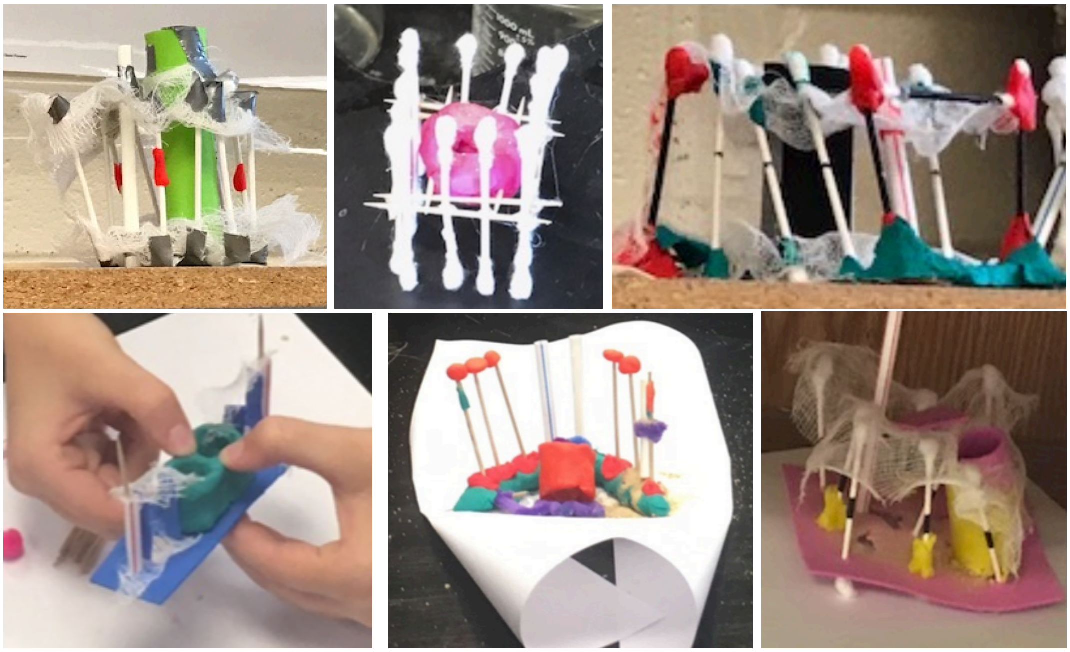

Figure 30. Examples of Students' Cell Membrane Prototypes

The pre-service teacher Mary also took note of original student ideas. When asked in her interview to describe a meaningful interaction with a student about their prototype, she said,

> **"***I had multiple interactions. I was just surprised at like how creative and different each group was with theirs, or at least class to class. Like sometimes I think within a class, students would look around and get ideas from each other. But like the one student who just like tied a rubber band around the multiple Q-tips, like that one crazy one in the front, and I was just like, "How did you guys come up with this?" And they, they were going through their thought process, and I was like, you know what, like I never would have thought that way… I just enjoyed interacting with them about like how they came up with their designs and why they thought that was the best design. And a lot of the times it had to do with like the money constraints, and a lot of times it had to do with they wanted it to look the coolest*" (Mary, Interview, 11.29.17)

Both the students and Mary commented on the creativity that the brainstorming and prototype construction allowed for. By working first independently and then as a group, students were able to first think of the own ideas and then leverage the strength of the group through collective brainstorming.

Summary

Mary's students demonstrated significant learning gains across all three learning outcomes. Significant learning gains in spite of low pre-test scores and the high Opportunity to Learn environment provided by Mary through her instructional planning resulted in her class being selected as an exemplar for further study. An analysis of the reflections on the EDIS unit by both Mary and her students resulted in five overall themes to which participants attribute their learning gains – two of which were identical themes across questions as thus are combined in the discussion chapter. These themes are also supported by classroom observations. First, when discussing their learning of the science content through engineering design content, the following two themes were identified: (1) Visualization of the process and (2) Hands-on building and creating. When identifying what they enjoyed the most about the EDP the following three themes emerged: (1) Designing and building the cell membrane prototype, (2) Redesigning and improving the prototype, and (3) Brainstorming and student creativity.

CHAPTER 6: DISCUSSION & IMPLICATIONS

The purpose of this sequential explanatory mixed methods research study was two-fold. First, to measure students' science content knowledge, understanding of the engineering design process, and their perceptions of engineering design before and after engineering design integrated science instruction. Second, to identify instructional factors at both the planning and implementation phases that may explain student outcomes in engineering design integrated science instruction. Kurz's (2011) Opportunity to Learn theory provided the framework through which I addressed the following research questions:

1. To what extent does engineering design integrated science instruction situated in an OTL model impact student learning outcomes in science (as measured by science content knowledge) and engineering design (as measured by understanding of engineering design and perceptions of engineering)?
2. To what extent does the qualitative data (unit plan, classroom observations, student responses & teacher interview response) from an exemplar of EDIS instruction within a high *Opportunity to Learn* environment, help to explain the quantitative results of student learning outcomes?

Results were obtained through a quantitative analysis, which consisted of dependent t-tests, HLM, and multiple regression modeling. Then, an exemplar EDIS unit, which provided a high OTL environment, was qualitatively analyzed in order to explain the quantitative results. This chapter presents a summary of the results and discusses the results in light of both the OTL framework and findings in previous studies. Finally, implications and suggestions for future research are presented.

Student Learning Outcomes

Science Content Knowledge Outcomes

Results show that across all classrooms, participant students demonstrated a statistically significant increase in their knowledge of their specific science content after the EDIS instruction. At the classroom level, all nine classrooms demonstrated positively-trending results, with seven of the classrooms demonstrating statistical significance. These results support the NRC's (2009) claim that the introduction of engineering into science classrooms can result in improved learning and achievement in science (p.49).

To a large extent, the findings from this study are also consistent with the findings reported in single-discipline outcome (SDO) studies that examined students' science content knowledge (e.g. Marulcu & Barnett, 2013; Mehalik et al., 2008; Schittka & Bell, 2011; Silk et al., 2009; and Wendell & Rogers, 2013). For example, in these studies, including the current study, pre and post-assessments were administered prior to and following an engineering design integrated science unit, and in all cases the results supported the hypothesis that students learned more about the science content that was presented through the engineering design process. While the outcomes were similar to the present study, several prior studies (e.g. Mehalik et al., 2008 and Wendell & Rogers, 2013) expanded upon their findings by comparing engineering design instruction with other instructional models (e.g. inquiry learning). A comparison group was not present in the current study but should be considered in future studies to further demonstrate the effectiveness of engineering design as an instructional model.

The current study also differs from the previously mentioned SDO studies, because it extends beyond science learning outcomes to address engineering design outcomes. For example, in Marulcu and Barnett's (2013) study, they found that fifth graders' understanding of simple machines increased significantly following involvement in a design-based science unit on simple machines. Despite the stated emphasis on engineering design and the presence of a mechanical engineer, an aerospace engineer, and an electrical engineer on the research team, engineering learning outcomes were not measured. This demonstrates a disconnect between the inter-disciplined nature of the activity and the single-disciplined assessment. Ideally, the measures of student learning should parallel those of the learning objectives. Without providing assessments in both disciplines, it is impossible to know whether or not the learning objectives were addressed and students learned both science and engineering design content.

A strength of the current study is its inter-disciplined outcomes – both science and engineering design. In the following sections, the current study's engineering design results are compared to the existing SDO engineering design literature, and then the current inter-discipline outcome study is compared to other inter-discipline outcome studies in the literature.

Engineering Design Outcomes

The NRC (2009) presented the following engineering-based benefits that students would potentially experience when introduced to an engineering infused science curriculum: (a) increased awareness of engineering and the work of engineers; (b) understanding of and the ability to engage in engineering design; and (c) interest in pursuing engineering as a career (p.49-50).

The results in the current study show that participant students met the first goal during the introduction of the EDIS unit. All pre-service teachers used the same presentation to introduce students to the field of engineering and to engineering careers. Next, all students were exposed to the engineering design process in a formal manner through an interactive presentation. Students then used engineering design process steps throughout the unit to solve an engineering design challenge. The work done by Crotty et al. (2017) suggests that this "*explicit integration*" instructional model (i.e. incorporating engineering design throughout the entire unit) results in greater student learning of engineering than when engineering is incorporated solely at the end of the unit in the form of a culminating project. Likewise, in the current study, students demonstrated a statistically significant increase in their understanding of engineering design following exposure to the EDIS unit, and thus achieved the second NRC's (2009) proposed engineering benefit of an integrated curriculum (i.e. developing an understanding of and the ability to engage in engineering design). Findings in this study bolster the argument for meaningfully incorporating engineering design throughout a unit, rather than merely using engineering design as an "add-on" activity.

Additionally, the NRC's third proposed engineering benefit – increase interest in pursuing engineering as a career – was evident in the current study through a comparison of students' pre-post survey responses on the Perceptions of Engineering Design instrument. Results indicate a statistically significant increase in students' Perceptions of Engineering Design (PED) following the implementation of the EDIS units, as compared to student responses before the EDIS units.

While the current study's results are similar to those reported in some previous studies demonstrating positive engineering design results (e.g. Capobianco et al., 2015; Crotty et al., 2017), this study differs in a significant way. For example, this study addresses student learning in both science and engineering design. As such, it extends beyond the single-discipline outcome studies to demonstrate the effectiveness of an integrated curriculum on outcomes across multiple disciplines. Examining this study's results in light of the inter-disciplinary outcome (IDO) literature is the subject of the next section.

Inter-Discipline Outcomes – Science & Engineering Design

The current study demonstrates that students' exposure to an engineering design integrated science unit can improve their learning outcomes in both science and engineering design. This finding is important for two essential reasons. First, this study contributes to the literature by demonstrating the importance of collecting data and reporting the results for learning outcomes across multiple content areas when implementing an integrated curriculum. As previously mentioned, one of the weaknesses in prior studies on engineering design integrated science instruction was the singular focus of the assessments (e.g. Marulcu & Barnett, 2013). Despite the integrated nature of the learning objectives and instructional practices, many studies reported student learning in only one content area – either science or engineering. However, the NRC (2009) stresses student learning benefits across content areas. As such, it is reasonable to expect that students should improve in both science and engineering after participating in an EDIS unit.

Second, this study contributes to the literature by presenting findings of statistically significant improvement across both content areas. These positive results support the work done by Apedoe et al. (2008), Selcen Guzey et al. (2016), and Chiu and Linn (2011). For example, Apedoe et al. (2008) following an eight-week chemistry and engineering design unit, students demonstrated both an increased knowledge in the chemistry concepts and an increased interest in engineering careers. While there are very few studies that demonstrate learning gains in both science and engineering, findings from this study should encourage educational researchers to continue to pursue engineering design integrated science instruction as a viable model for achieving the goals set forth in the national reform documents (NGSS, 2013; NRC, 2012).

However, it is important to note that not all IDO studies have found similar positive results (e.g. Berland et al., 2013; Tran & Nathan, 2010). For example, Tran and Nathan (2010) reported that after the intervention, participant students demonstrated smaller achievement gains in science and math as compared to peers who were exposed to different curriculum. Tran and Nathan's (2010) study relied heavily on one quantitative data source. As such, they were not able to account for the smaller gains in student learning following the intervention. A lack of an explanation for the negative results makes it difficult to compare their study to others. The study would therefore have benefited from the recommendations put forth by several researchers (Crotty et al., 2017; Mehalik et al., 2008;

Wendell & Rogers, 2013) to include qualitative data (i.e. students' perceptions of instruction or teacher interviews) and analysis to further explain the quantitative findings.

Overall, results from this study contribute to the scarce body of research on measuring multiple outcomes for integrated science and engineering design interventions. The inclusion of both science and engineering design outcomes in this study should encourage future researchers to consider including measures of student learning across outcomes. Furthermore, results in this study provide support for the vision put forth in *The Framework for K-12 Science Education* (NRC, 2012) and the *NGSS* (NGSS Lead States, 2013) to increase the integration of engineering design in science classrooms across the United States.

Explanations for Student Learning Outcomes

While the positive learning outcome results are encouraging, it is important to explore potential factors that contributed to learning gains among students for other researchers to replicate the study and for educators to develop their own EDIS units. In the next section, I have provided possible explanations for student learning outcomes, both during the instructional planning phase (i.e. OTL factors) and during the implementation phase (i.e. visualization, opportunity to redesign, etc.).

Instructional Planning Factors

Results from the quantitative analysis indicate that not all pre-service teachers provided the same type of OTL environment for students, as measured by their instructional planning (i.e. content coverage, quality of instruction, and time). It should be noted that content coverage and quality of instruction were assessed purely from the pre-service teachers' unit plans. Instructional time was also initially measured based on the allotted time described in pre-service teachers' unit plans. However, a few teachers ended up extending their unit and so their "time" variable was adjusted accordingly. Because the instructional time was largely derived from the pre-service teachers' unit plans and only minor adjustments (less than 90 minutes) were made to a few pre-service teachers' time variable, time was considered an instructional planning factor along with the other two OTL components.

In this study, EDIS units were grouped into high and low OTL environments to determine if there were differences in learning outcomes across groups and possible explanations for learning outcomes. The statistical modeling revealed that the type of OTL environment may impact student learning outcomes, particularly with regard to science and engineering design content knowledge.

Of particular interest is the finding that high OTL environments were especially beneficial for students who initially performed poorly on the pre-assessments. The multiple regression models revealed that despite differences in pre-test scores, students in the high OTL environment had similar post-test scores. These results occurred for both the science content and engineering design content learning outcomes. Other studies found that when implementing engineering design in science classrooms, it is the students who are traditionally low-performers in science that benefit the most from this instructional model (Guzey et al., 2016b; Mehalik et al., 2008; Silk et al., 2009). For example, Silk et al. (2009) found that the students who demonstrated the greatest learning gains in science reasoning following an engineering design activity were those students who scored the lowest on the pre-assessment. This finding is similar to that of Guzey et al. (2016b), which showed that the engineering design integrated science unit was particularly powerful for learning among students with disabilities. Based on results in the current study and those reported in previous studies, engineering design integrated science instruction, in the presence of a high OTL environment, may serve as a teaching method that provides equitable instruction for all students in science classrooms.

In this study, the high OTL environment is one in which both the science and engineering design content is integrated throughout the unit (i.e. learning objectives, instructional practices, assessments, etc.). A better understanding of the high OTL environment can be gained through closely examining one example – Mary's Creating a Cell Membrane EDIS unit. Mary's detailed and comprehensive EDIS unit plan exhibited the instructional planning of a high-quality unit that spanned four 90-minute class periods. Additionally, Mary's EDIS unit demonstrated a moderate to high degree of integration between the science content and the engineering design content. Specifically, her unit was more science focused than a balanced integration of content areas (Mumba et al., 2017). This finding was also confirmed by Mary in her interview. Although Mary's EDIS unit could have exhibited a higher degree of content integration, her unit was not an "*add-on integration*" unit as defined by Guzey et al. (2017b). According to Guzey et al. (2017b) "*add-on integration,*" in which the engineering design project occurs at the end of a science unit, is the most common, but least effective, integration strategy for teaching both science and engineering design content. Mary's EDIS unit exhibited features of *"explicit integration"* in which the engineering design process is embedded throughout the unit, and students learn about the science content through the design challenge (Guzey et al., 2017b). *"Explicit integration"* and *"implicit integration"* are the two instructional strategies that have been associated with higher learning gains in science and engineering design content knowledge, compared to the "*add-on*" or "*culminating project*" models (Guzey et al., 2017b).

Overall, these findings suggest that with a high degree of content integration, a high-quality unit, and multiple EDIS instructional days, low-performing students may perform at levels similar to their peers in both science content and engineering design content, and thus reduce the achievement gap following engagement with EDIS units. As such, these factors – content coverage, quality of unit plan, and instructional time – serve as instructional planning factors that provide potential explanations for student learning gains. Additional explanations for student learning gains, beyond the high OTL environment, are presented in the following section.

Implementation Factors

An exemplar EDIS unit was examined to address the second research question, and to provide potential explanations for the large learning gains observed for low-performing students on the pre-test in a high OTL environment. The use of responses from participants – both student and the pre-service teacher –combined with the observation field notes and unit plan analysis, form a more complete picture of what occurred during the EDIS unit instruction. Throughout the qualitative analysis of student reflections and pre-service teacher interview responses, the following four themes emerged as potential factors that may have contributed to student learning outcomes – visualization, hands-on creation of prototypes, redesigning, and creatively brainstorming. These possible explanations were gleaned from the data analysis of an exemplar high OTL EDIS unit instruction.

Visualization. The notion that creating the 3D cell membrane allowed students to better understand the science content was a reoccurring sentiment. Approximately half of Mary's students indicated that it was the visualization of the cell membrane or the cell membrane's functions that enabled them to understand science and engineering design content knowledge. In her interview, Mary also said that the 3D model provided benefits that are absent in a 2D model. Classroom observations also revealed that students used their models to articulate their ideas and conceptions about the science content.

The importance of visuals for student learning has been well documented in other studies. For example, central to the creation of the engineering design unit in Chiu and Linn (2011) was an adherence to the Knowledge Integration (KI) learning theory, which provides an explanation for how students make connections (p.3). One of the KI principles is "making thinking visible" (Linn & Hsi, 2000). In the *Airbags* unit, visualizations were an essential part of the unit, based on the rationale that students will integrate their understanding through modeling (Chiu & Linn, 2011). Similarly, Chao et al. (2017) recommended engaging students in model manipulations and simulations, as a means to facilitate connections between engineering and science. As a whole, the findings in this study and from previous studies suggest that visualizations and models may serve an important role in student learning of both science content and engineering design content.

Hands-on creation of prototypes. If the prior explanation of visualization were to stand on its own as the sole contributor to student learning, it could be argued that the power of the unit was merely the impactful nature of visual models. However, approximately a third of Mary's students also attributed their learning to the opportunity to physically build and create the prototypes in their engineering design tasks. Through classroom observations, it was evident that students enjoyed this part of the engineering design process. Beyond merely enjoying the process, approximately 10% of the students specifically stated that the building of the prototype assisted in their learning of the cell membrane, because successful construction was predicated on an understanding of the science content. The ability to make connections between, and apply knowledge from, one content area to another is an indicator of an "expert" designer (Crismond, 2001) and as such, it is an important skill to foster in students.

However, research suggests that some students do not value components of the engineering design process that foster connections between content areas (Berland et al., 2014). Thus, it is an important finding that students enjoy the building phase, and also value its role in making connections between science and engineering.

Redesigning and improving the prototype. Based on the previously stated two explanations for student learning outcomes, one may conclude that it is the hands-on building of a model that mediated student learning of science and engineering design knowledge. The suggestion that these student learning gains would exist in the absence of EDIS instruction is refuted by the presence of this factor - redesigning and improving the prototype - identified by students. In the open-ended reflection question, 22% of students stated that they specifically enjoyed the redesigning phase of the EDP. Students also suggested that they enjoyed the opportunity to learn from their mistakes and to embrace failure. During the classroom observations, it was noted that throughout the engineering design process students engaged in "informal" redesign. As students constructed their prototypes, they would correct apparent flaws or use materials not included in their initial design sketch. Consistent with previous literature (Berland et al., 2014), student learning of engineering design content may be partially explained by student's enjoyment of the iterative nature of the DP and the redesign phase.

Brainstorming and student creativity. When asked what they enjoyed the most about the EDP, the third most common response was that students appreciated the opportunity to brainstorm, both individually and in groups, and the chance to exhibit their creativity. Student creativity was observed during EDIS instruction. There was great variation amongst the prototype designs and the materials used to construct the prototypes. This finding is supported by previous studies on science and engineering design integrated instruction in which the researchers attempted to explain the improvements in student learning outcomes (Guzey et al., 2016b; Mehalik et al., 2008). For example, Mehalik et al. (2008) hypothesized that student choice and flexibility to pursue their own ideas contributed to science learning gains.

Summary. The following four elements emerged as possible explanations for student learning outcomes – visualization, hands-on building of prototypes, redesigning, and creatively brainstorming. The final two explanations are factors that occur particularly in the engineering design process, and as such, move the activity beyond merely the building and creating of models. These four components should be considered when designing novel EDIS units for science classrooms.

Conclusion

The findings from the quantitative analysis indicate that when pre-service teachers, trained in EDIS instruction, plan for and enact EDIS units in their high school science classrooms, students can learn both the intended science content and engineering design content and improve their perceptions of engineering design.

While there were common elements across the EDIS units that pre-service teachers taught, there were differences in content coverage, quality of unit, and length of instructional time. Although learning gains were seen across all pre-service teachers' classrooms, results varied between high and low OTL environment classrooms, indicating that these instructionally planning factors (i.e. content coverage, quality of unit plan, and instructional time) may help to explain student learning outcomes. Particularly striking is the finding that in the presence of a high OTL environment, students who scored very low on the pre-tests for science and engineering design knowledge subsequently had very high post-test scores. As such, providing students, who perform low on pre-assessment, with an EDIS experience in a high OTL environment may help to ameliorate learning differences between low and high-performing students. Specific factors from EDIS unit that occurred during the implementation phase, which may have resulted in student learning include: the visualization of the processes through models, the building of prototypes, the ability to learn from mistakes through redesign, and the opportunity to creatively brainstorm solutions.

This study and prior research suggest that student interest and preference for particular elements of the design process such as brainstorming, building, and redesign may mediate student learning of engineering design content (Berland et al., 2014). Moreover, through the use of visualizations, students can make connections between the science and engineering design content (Chao et al., 2017; Crismond, 2001), which may result in strong learning gains across content areas. Thus, science teachers should intentionally incorporate these elements, along with a strong OTL environment into their EDIS units.

Limitations

I acknowledge that there are some limitations in this study. First, the current study had a small sample size of the pre-service teachers (n=9). The small sample size means that HLM results must be analyzed with caution. And for this reason, additional modeling analysis, multiple regression, was performed.

Second, only one researcher observed many of the lessons in person. While two researchers independently coded and compared results during the quantitative analysis, due to time and budget restrictions, only one researcher participated in the qualitative analysis. In order to reduce bias, the researcher kept a methodological journal throughout the quantitative and qualitative analysis and engaged in several practices to reduce common threats to validity in qualitative research (see Chapter 3).

In order to provide additional support for the impact of engineering design integrated science instruction on student learning outcomes, ideally this study would have included a control classroom from which to compare student learning outcomes. However, time and resources did not make this possible, and this is a suggestion for future research studies. Additionally, time and resources limited the number of teacher factors that were examined. There are many teacher factors that present potential avenues of study (i.e. teachers' content knowledge and teachers' self-efficacy in teaching engineering design).

It should also be noted that the qualitative analysis was performed on one exemplar classroom to highlight the EDIS instruction in a high OTL environment. While this is not a limitation of study, as the intention of qualitative is never to generalize, it is worth drawing the readers' attention to the issues.

Implications & Future Research

This section presents the implications of the findings on three areas of study – research on integrating engineering design into science classrooms, science teacher education programs, and engineering design integrated science teaching and learning of engineering design in science classrooms. The section concludes by presenting directions for future research in light of the current study.

Research on Integrating Science & Engineering Design

Results from this study add to the newly developed body of research on integrating engineering design into science classrooms. First, findings from this study contribute to the literature by examining both science and engineering design learning outcomes. Very few studies present student learning outcomes for both science and engineering design content areas (e.g. Apedoe et al, 2008). Of those studies that report both learning outcomes, some have found negative results (e.g. Tran & Nathan, 2010), and yet others have found mixed results in which student learning improved in one content area but not in the other (e.g. Glancy et al., 2017). This study adds to the few studies that examined both student learning in engineering design and science, as well as found positive results for outcomes in both content areas (e.g. Selcen Guzey et al., 2016; Chiu & Linn, 2011). As such, this provides additional support for the integration of engineering design and science, and demonstrates the necessity to measure outcomes in multiple content areas when studying an integrated intervention.

This study also contributes to the research on integrating engineering design into science classrooms by exploring potential explanations for the learning gains. Many of the studies that address student learning outcomes do not provide explanations for the learning outcomes (e.g. Capobianco et al., 2015; Marulcu & Barnett, 2103). By not providing explanations, it is difficult for readers to ascertain the qualities of the intervention that resulted in the presence (or absence) of learning gains. Many researchers are aware of this gap and have called upon future studies to examine the reasons that may explain student learning (Crotty et al., 2017; Wendell & Rogers, 2013). This study attempted to contribute to this gap in the research by providing potential explanations for student learning both at the instructional planning and the implementation levels. This study's findings largely support the few student-outcome studies that do examine explanations for learning gains (e.g. Guzey et al., 2016b; Mehalik et al., 2008), and contribute a deeper understanding of the potential factors that should be included for successful EDIS units. Additionally, this study, raises the awareness of the need for future researchers to include information on teacher factors - such as the degree to which engineering design and science are integrated - into their description of their units. Teacher factors, particularly those related to the implementation of a unit are often assessed using qualitative data and analyses procedures. The sequential mixed methods research design is often used to examine quantitative results in light of qualitative analyses (Creswell & Clark, 2011). The present study therefore also contributes to the existing literature by providing a model of how to use both quantitative and qualitative analyses to present a complete picture of student learning occurring in a classroom.

This study also supports the use of the Opportunity to Learn (Kurz, 2011) as a theoretical framework that can assist researchers in the understanding of student learning in EDIS contexts. OTL theory is predominantly used in educational research, when examining the equity of learning environments and assessments. However, this study demonstrates that the OTL theory can be successfully used to help explain learning outcomes in engineering design integrated science classrooms.

Lastly, this study contributes to the current research on engineering design in science classrooms by reporting on an underrepresented population of teachers in the literature, pre-service teachers. Presently, there are no studies that examine how pre-service teachers learn about integrating engineering design into their science instruction and how they then implement these units during their clinical student teaching experience. However, science teacher education programs are increasingly being called upon to train pre-service science teachers in engineering design integrated science practices (NRC, 2012). Implications of this research study on the field of science teacher education are provided in the following section.

Overall, this study contributes to the literature by addressing three major gaps: (1) a lack of studies which include both science and engineering design learning outcomes; (2) a need to incorporate qualitative analyses to explain quantitative findings on student learning outcomes; and (3) a lack of studies on pre-service science teachers' planning of and teaching EDIS lessons.

Science Teacher Education Programs

Although results in this study cannot be generalized due to a small number of participants, the findings have implications for science teacher education. For example, these findings suggest that pre-service teachers were able to plan and teach high quality EDIS units that positively impacted student learning outcomes. Participant pre-service teachers were able to create and enact these unit plans following the explicit inclusion of engineering design into their science methods course. As such, it is important for teacher education programs to provide explicit instruction on developing and teaching EDIS units in science classrooms. Providing pre-service teachers with formal exposure to engineering design and integrating engineering design into science classrooms, is a charge to put forth in *The Framework for K-12 Science Education* to science education programs (NRC, 2012, p.257-258). These findings also suggest that within teacher education programs, science teacher educators should make teachers aware of the various factors that may influence student learning in EDIS contexts. For example, results of this study suggest that a high-degree of integration between engineering design and science content areas may prove beneficial for improving student learning. Therefore, science teacher educators could scaffold EDIS instruction by first training science teachers to identify the degree of integration in pre-existing EDIS units and then how to adapt the instructional materials to better integrate the two content areas. Next, teacher educators could assist pre-service teachers in creating their own EDIS unit plan, with a high degree of science and engineering design integration. Teacher education in EDIS is crucial both at the pre-service and in-service levels in order for the vision of NGSS to become a reality (NRC, 2012, p.241), and for the students to fully reap the benefits of integrating engineering design into science classrooms.

Teaching & Learning of Engineering Design in Science Classrooms

Results from this study show that when students are provided with an opportunity to learn science content through engineering design, the students may demonstrate gains in the following learning outcomes – science content knowledge, engineering design knowledge, and perceptions of engineering design.

It is crucial that these engineering design integrated science units support science content learning because they are occurring within the context of a science classroom. Thus, teachers will likely be more willing to spend the time and resources devoted to enacting an EDIS unit, if they know that students will likely learn the science content through the engineering design process. A better understanding of both science and engineering is a central component to the vision presented in *The Framework for K-12 Science Education,* which states that,

> “students will acquire knowledge and skill in science and engineering design through a carefully designed sequence of learning experiences. Each stage in the sequence will develop students’ understanding of particular scientific and engineering practices….while also deepening their insights into the ways in which people from all backgrounds engage in scientific and engineering work to satisfy their curiosity, seek explanations about the world, and improve the built world.” (NRC, 2012, p.247)

This vision suggests that it is not only essential to increase students’ understanding of science and engineering, but that in doing so, students may develop a more favorable view of the science and engineering design fields. As cited by the *Framework for K-12 Science Education,* research has supported the notion that student interest in science is a strong indicator of future science career attainment (Tai, Liu, Maltese, & Fan, 2006). It is thus logical to extend this argument to engineering design – student interest in engineering may lead them to pursue careers in engineering. The current study provides a model for high school teachers on how to improve both students’ content knowledge of engineering design and their perceptions of engineering design.

By demonstrating student learning gains in science content knowledge, engineering design knowledge, and perceptions of engineering design, this study provides an argument for teachers to teach science through an integrated engineering design approach. The results show that even if pre-service teachers plan for and enact an EDIS unit that provides a low OTL environment, high school students will still demonstrate learning gains. This finding may be helpful in encouraging principals and instructional coaches, who are hesitant about their teachers' pedagogical abilities to enact an EDIS unit. Results from this study demonstrate that even a one-day EDIS unit with low content integration and low overall quality can positively impact students in both science and engineering design. While this type of instruction is not ideal, students can learn in these environments, and the current study provides some factors that teachers can practically focus on to improve student learning outcomes during an EDIS unit.

For example, this study shows that teachers should strive to create and/or enact high-quality, multi-day, EDIS units that provide a high degree of integration between science and engineering design content areas. Teachers should also include visual models, the building of prototypes, the redesign phase, and the brainstorming phase in their EDIS units. Results from this study show that while high school students demonstrated learning in both low and high OTL environments, providing students with a high OTL environment can be particularly beneficial for students who scored low on the pre-assessments. As such, this study also has potential implications for teaching and learning for students who demonstrated low performance at the beginning of the intervention. Moreover, these findings are aligned with the NRC's foundational goal of promoting equity among all students. *The Framework for K-12 Science Education* explicitly states, "Not only should all students be expected to attain these standards, but also work is needed to ensure that all are provided with high-quality opportunities to engage in significant science and engineering learning" (NRC, 2012, p.29). Findings from this research study provide a potential path for achieving this goal.

Recommendations

Findings from this study present areas for future studies on integrating engineering design into science classrooms. Below are both methodological recommendations and suggestions for future areas of research.

First, the present research demonstrates the importance of assessing both science and engineering design learning outcomes when enacting an engineering design and science integrated unit. As such, future studies which include inter-disciplinary instructional units should ensure that the outcome measures reflect the totality of the content taught in the unit. Without measuring student achievement in all of the content areas represented in the unit, it is impossible to know whether or not the learning objectives were met.

In addition to providing the results on student learning, this research study attempted to provide potential explanations for why the student learning occurred. This area of research is particularly under-developed, and future studies should consider including hypotheses as to why the learning occurred. Future studies could achieve this goal by either quantitatively comparing the learning outcomes with those from a control group or through an in-depth qualitative analysis of the implementation of the EDIS unit. Addressing the factors that contribute to student learning in EDIS contexts is important for teacher education and for the teaching and learning of science and engineering design.

While many previous studies have cited design-based learning in their rationale for creating their integrated engineering design unit (e.g. Silk et al., 2009), they did not use design-based learning to inform their interpretation of the results. Leveraging findings from design-based learning provides researchers with factors that influence student learning, which can then be tested in EDIS contexts.

In addition to using design-based learning as a source of potential factors that may influence student learning in EDIS contexts, future research should consider many other teacher factors, such as teacher's understanding of engineering design or teacher's self-efficacy in teaching engineering design. Prior research suggests that science teachers often hold misconceptions about engineering design (Antink-Meyer & Meyer, 2016) and demonstrate vastly different levels of subject matter knowledge (Hynes, 2012). Given that teachers' understanding of engineering design is varied, and teacher knowledge and understanding has been shown to impact teaching practices (Blanchard, Southerland, & Granger, 2009; Capps et al., 2012), teacher understanding of engineering design is an important factor to consider when assessing student learning. Thus, studies focusing on the implementation and integration of engineering design in science classrooms, should also consider other teacher factors such as the teacher's understanding of engineering design. Future research should also address teachers' self-efficacy in teaching engineering design. Previous research shows that many science teachers exhibit low-self efficacy when teaching engineering design (Capobianco, 2011; Wendt, Isbell, Fidan, & Pittman, 2015). Furthermore, teacher efficacy beliefs have been identified as an extremely important variable in predicting teachers' behaviors in the classroom and student achievement in science (Cakiroglu, Capa-Aydin, & Hoy, 2012). If teachers do not feel comfortable in teaching engineering design, then it is less likely that they will enact a well-integrated science and engineering design lesson. Therefore, future EDIS research should both measure teachers' self-efficacy and attempt to increase their self-efficacy in teaching engineering design and the extent to which such instruction impacts student learning outcomes.

While this study focused on high school students in science classrooms, it is important to expand the field by studying different contexts. Future studies should examine EDIS instruction at both the elementary and middle school levels as well as comparing results across grade levels. In this study, pre-service teachers taught in high school chemistry, biology, earth, and physics classrooms. However, the study did not focus on the similarities and differences between these subject areas. As such, future studies should also compare student learning outcomes across subject areas. Additionally, this study focused solely on engineering design integrated science learning within science classrooms. Future areas of study include both after school programs and summer camps. Addressing these lines of inquiry will provide researchers, science teacher educators, and teachers with a better understanding of engineering design integrated science instruction in schools.

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Appendix A

Science Content Knowledge (SCK) Test

(The science content is specific to the lesson taught. Therefore, this is an example from one pre-service science teacher.)

1. Compare and contrast artificial tissues and real tissues.

2. Based on what you know, what type of tissues do you believe would be most easily damaged and how would that tissue regenerate?

3. Explain whether or not you believe that artificial tissues could be used as substitutions to human tissues.

4. What types of tissues could be engineered and why? (Include which of the 4 major types, as well as more specifically the tissues within each of these categories.)

Appendix B

Student Understanding of Engineering Design Process (SUEDP) Test

1. What is engineering?

2. Describe the engineering design process. Use a diagram to illustrate your answer.

3. Is the engineering design process linear or cyclical? Explain your answer.

4. What is the difference between the scientific method and the engineering design process?

5. What is a design challenge in engineering?

6. What is a design solution in engineering?

7. What did you like most about the engineering design process? *

8. How did the engineering design process help you learn more about tissues? *

** Represents a question that was only asked on the post-test.*

Appendix C

Perceptions of Engineering Design (PED) Survey

Please respond to each of the statements below by choosing the response option that best reflects your views on engineering design. The response options are: 1=Strongly Disagree (**SD**) 2=Disagree (**D**) 3=Neutral (**N**) 4=Agree (**A**) 5=Strong Agree (**SA**).

Statements	**SD (Strongly Disagree)**	**D (Disagree)**	**N (Neutral)**	**A (Agree)**	**SA (Strongly Agree)**
I like engineering.	1	2	3	4	5
I like using engineering design to learn science.	1	2	3	4	5
Engineering challenges are fun.	1	2	3	4	5
I would rather do engineering than regular science.	1	2	3	4	5
I learn more science when using engineering design.	1	2	3	4	5
Learning science through engineering design has not changed some of my ideas about how the physical world works.	1	2	3	4	5
It is easy for me to explain how science concepts apply in everyday life through engineering design.	1	2	3	4	5
I am very comfortable designing engineering projects in science lessons.	1	2	3	4	5
I am confident in my ability to use engineering design skills to reason logically about the physical world.	1	2	3	4	5
Engineering design is **NOT** an effective tool for learning science.	1	2	3	4	5

Appendix D

Engineering Design Integrated Science Classroom Observation Field Notes (Example)

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: ________________

<u>Summary:</u> This is the third day of engineering design. Students review the content and they then work on their design portfolios.

- Resources:
  - Video footage
  - Handouts – review sheet, design portfolio
  - PowerPoint presentation

Bolded only text is the text on the PowerPoint slide.
*****AN: analytic notes.***

Time	Description of events
	**Note: All names are pseudonyms.*
8:55	Board: Agenda 1. cell membrane and cell transport notes 2. Engineering design intro steps (1-4) The students are in their seats. Mary provides them with a review sheet of cell transport. ***(AN: This is one that I gave her yesterday.)*** Mary goes over the review sheet. She asks questions about the content and so the students help her to fill it out. As she is writing on the paper, students copy down the notes on to their own papers. Students all appear to be engaged and paying attention.
9:06	Mary then has the students look to the side board to show them the list of everything that they need to include in their model. Components 1. hydrophilic head (lipid bilayer) 2. hydrophobic tail (lipid bilayer)

	3. channel protein 4. Carrier protein 5. Cholesterol Functions: 1. Simple Diffusion – CO_2 and O_2 through lipids (no energy) 2. Facilitated Diffusion – Water through channel proteins (no energy) 3. Active Transport – glucose and mineral ions through carrier proteins (with energy) Mary then says that they are going to work on step 4. She says they are going to select the best design and then when the students are ready, they can move to the back of the room to get the materials. Students asks for a list of the groups. They move over to their groups, and they begin to talk. A few students ask if they need to show the cell membrane. Mary then asks the students for their attention. Mary, "If the cell membrane goes all of the way around the cell, you only need to create a small section of the membrane with lipids and 2 proteins." " One student says that she is confused about the active transport motion. The mentor teacher explains this to her. He is sitting at the materials table. Mary is walking around the room and explaining how the students are going to create the active transport and how they are going to put energy into the active transport. Many of the groups are still discussing their prototypes. One group moves over to the materials table to buy their supplies. They provide the mentor teacher with the slip, and they obtain their materials. Mary is now talking with students about their drawing. She is explaining to them how their proteins will span across the membrane. She is also telling the students that she understands that they don't have to make the entire membrane. There is another group that is buying materials. They are discussing that they might want to buy their materials in multiple trips. Students are asking about the materials and the different quantities that they might provide.
9:25	Mary gets out the scissors and tells students that they can have these for free. Students are all in their groups and appear to be engaged in the assignment. The group next to me is still sketching their designs. Mary then tells them that they can test their prototypes with the substrates of water, sand, the marble, and the pom poms.

9:41	Mary is walking around to different groups and is talking with the students about their designs. Some of the students want to return their supplies. Mary said in the past that they can return their supplies if they have not used them. One student asks if they can buy paper. The mentor teacher says that he will sell it to them for 50 cents. Several groups move to the materials table to return their materials. The mentor teacher is filling orders and making returns. Most of the groups are surrounding the materials table. Most of the groups are working on their design and are beginning to create their prototypes. Students in two different groups are comparing how much they have spent. ***(AN: Students appear to be competitive as to how who will spend the least.)*** Mary is asking a group how they are going to make their active transport use energy. One group asks if they have access to an exacto knife. The mentor teacher says that it will be a $1. The group in front of me is using cheesecloth, tape, playdoh, q-tips, and toothpicks. There is one group that is complaining because when they returned some of the materials, they lost some money. All of the student groups are working on the building of their prototypes. Most of the groups are using toothpicks and q-tips to show the lipid bilayer. There are a lot of student conversations. They are mostly all about the project at hand. There is not a lot of off-topic conversation. The mentor teacher and Mary are walking around to assist the groups. The mentor teacher is telling one group that they need to plan better before buying supplies because they are complaining that they don't have enough money. One of the students is arguing that her brother works in aerospace engineering and they have to try different things. ***(AN: They are laughing, so they are mostly joking, but I think that this is a good sign that they are connecting their real world knowledge of engineering to this project.)*** The group in front of me is working with play doh to create their hydrophobic heads of the phospholipid bilayer. They just bought more play doh. Mary makes an announcement that they have 15 minutes until they need to clean up. She tells them that they are going to have some more time to work on their prototype, and they are going to test them. She tells them that they can come in during CHAT to work on their project. The mentor teacher tells Mary that they should have the students put their names on a blank piece of paper so that they can put their materials on it.

10:07	The group in front of me is making their prototype now primarily of playdoh. They are talking amongst each other about how they can revise their design. One student traded the mentor teacher with food so that she can get playdoh to play with during the school day. Mary is talking with the group in front of me. Students are debating how to attach something to the cheesecloth. Mary reminds them that they need to have the lipid bilayer as well. They say they are still building. Mary shows them how they can use toothpicks to more securely structure their design. There is a low volume of noise in the classroom. Mary gives them a 5-minute warning until clean-up. The mentor teacher starts singing a song with another student. There are 7 groups and all of them are working on their building of prototypes. The students begin to put their materials on their blank piece of paper, so that they have their designs for next class. Another group moves to the materials table and asks for additional tape. Students are moving around the room. Mary tells people that there is no rule that they can't trade between groups.
10:19	Several groups are still working. The noise level in the room rises. Mary asks the students to give her back the marbles and the other substrates. Students pack up their materials and their belongings. Mary tells them that they are doing an awesome job. Students are talking about how much "money" they spent on their projects. Some of the students are using the plastic wrap to store their play-doh so that it doesn't dry out.

Appendix E

Pre-Service Science Teacher Interview Protocol

1. 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.)

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

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

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

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

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

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

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

Appendix F

Curriculum Quality Rubric (Guzey et al., 2016a)

Appendix: STEM Integration Curriculum Assessment (STEM-ICA)

Reviewer Name:
Curriculum Name:
Date Curriculum Reviewed:

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 **five-point scale from 0 to 4** describing the extent to which the unit meets the characteristics

1. 0: Not present
2. 1: Weak
3. 2: Adequate
4. 3: Good
5. 4: Excellent

NA/DK

- Zero means none of the characteristics described in the question are reflected in the curriculum unit.
- Four indicates that all of the characteristics described in the question are reflected in the material.
- The NA means "Not Applicable" and DK means "Don't Know." These should only 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.

I. A Motivating and Engaging Context

Does the curriculum unit....	*No*	*Somewhat*	*Yes*
Allow students to make sense of the situation based on extensions of their own personal knowledge and experiences?			
Engage and motivate students from different backgrounds?			
Provide a context with a compelling purpose (what, why, and for whom)?			
Include global, economic, environmental, and/or societal contexts?			
Include current events and/or contemporary issues?			
Provide opportunities to apply engineering process in partially or completely realistic situations?			

1.1. 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:

II. An Engineering Design Challenge

Does the curriculum unit…	*No*	*Somewhat*	*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?			
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?			

2. 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:

III. Integration of Science Content

Does the curriculum unit…	*No*	*Somewhat*	*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?			

3. 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:

IV. Integration of Mathematics Content

Does the curriculum unit…	*No*	*Somewhat*	*Yes*
Address state standards in mathematics at levels that match test specifications and beyond?			
Integrate mathematics concepts that are grade level appropriate?			
Require students to learn, understand, and use fundamental mathematics concepts, particularly in data analysis and measurement, necessary to solve the engineering challenge?			
Promote coherent understanding of mathematical thinking?			

To what extent does the curriculum unit integrate mathematics 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

V. Instructional Strategies

Does the curriculum unit…	*No*	*Somewhat*	*Yes*
Contains lessons 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)?			
Include explicit 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?			

4. 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:

VI. Teamwork

Does the curriculum unit…	*No*	*Somewhat*	*Yes*
Require students to collaborate with others?			
Include opportunities for students to demonstrate individual responsibility while working in a team?			
Build in instructional strategies that encourage positive team interactions and the five elements of cooperative learning?			
Require that each member of the team is needed for completion of the activities/tasks?			

6. How well does the curriculum unit enable students to develop teamwork skills?
NA/DK 0 1 2 3 4
Describe the evidence that supports your ratings:

VII. Communication

Does the curriculum unit…	*No*	*Somewhat*	*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 presentations to the client, written such as a memo to the client, technical communication, or with visual aids such as schematics)?			
Encourage multiple modes of representation (real life situations, pictures, verbal symbols, written symbols, manipulatives/concrete models) within communication of learning?			
Include a requirement for argumentation strategies?			

7. How well 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:

VIII. Performance and Formative Assessment

Does the curriculum unit include assessments that…	*No*	*Somewhat*	*Yes*
Are closely aligned with the learning objectives and goals and content from the multiple disciplines of STEM?			
Are tied meaningfully to state standards and test specifications and, when possible, go beyond these specifications?			
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?			

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:

IX. Organization

Does the curriculum unit…	*No*	*Somewhat*	*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?			
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?			

9. How well is the curriculum unit organized?
NA/DK 0 1 2 3 4
Describe the evidence that supports your ratings:

OVERALL RATING

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 judgment 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:

Appendix G

Mary's 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.

<u>PART I: Learning Objectives</u>

<u>Essential Questions:</u>

How does the cell membrane help maintain homeostasis inside of the cell?
What are the steps of the Engineering Design Process?

<u>Virginia Standards of Learning (SOLs):</u>

Primary SOL's

BIO.3 The student will investigate and understand relationships between cell structure and function. Key concepts include

d) the cell membrane model

e) the impact of surface area to volume ratio on cell division, material transport, and other life processes

BIO.4 The student will investigate and understand life functions of Archaea, Bacteria and Eukarya. Key concepts include

a) comparison of their metabolic activities

b) maintenance of homeostasis

d) human health issues

Secondary SOL's

BIO.1 The student will demonstrate an understanding of scientific reasoning, logic, and the nature of science by planning and conducting investigations in which

f) sources of error inherent in experimental design are identified and discussed.

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.

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

- 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:

Lesso n Segme	Materials	Instructional Sequence	Teacher/Student Actions

nt & Time Est.			
Introduction 10 min	• 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 min	• 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 10 min	Venn-Diagram handout	• **Assessment with partners:** Venn diagram (3 part) comparing and contrasting simple diffusion, facilitated diffusion, and active transport • Assign Steps 1 & 2 on engineering design workbook for homework.	Teacher: • 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 min	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 both?	Teacher: • Hand out assessment • Go over answers with students while they self-grade. • Collect assessment Students: • Answer assessment questions • Grade their own papers.
Body 70 min	• Engineering Design Packets • Styrofoam balls	• Refresh the students on what their design challenge is and remind them that they should have done steps 1-2 on	Teacher: • Refresh students on their design task and the different steps of engineering design.

	• 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	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 most likely won't happen until next class).	• 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
Closure 5 min		• 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
	• Pipe cleaner
		• 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
			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.

	• Aluminum Foil • Play-doh • Q-tips • Sand • Water • Marbles • Pom-Poms	• Facilitated diffusion • Active transport • Each group will be given a group evaluation	• Students should present with their groups • Students should sit quietly while other groups are 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	Teacher: • Facilitate review Students: • Participate in review

		to be transported across the cell membrane, and the types of • Review engineering design process	
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 Resources 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 membrane, and release it.	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
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	The groups explanation was somewhat thorough,	The groups explanation was not adequate and they	/3

	every part of their cell membrane model	but they missed one to two	missed the explanation of three or more of the	
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

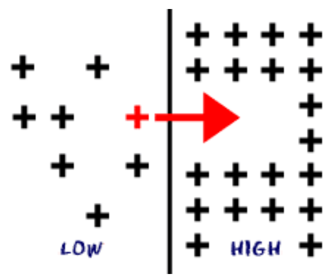
Resource A - Pre-Assessment

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?

Section C
Please respond to each of the statements below by choosing the response option that best reflects your views on engineering design. The response options are:
1=Strongly Disagree (SD) 2=Disagree (D) 3=Neutral (N) 4=Agree (A) 5=Strong Agree (SA)

Statements	SD (Strongly Disagree)	D (Disagree)	N (Neutral)	A (Agree)	SA (Strongly Agree)
I like engineering.	1	2	3	4	5
I like using engineering design to learn science.	1	2	3	4	5
Engineering challenges are fun.	1	2	3	4	5
I would rather do engineering than regular science.	1	2	3	4	5
I learn more science when using engineering design.	1	2	3	4	5
Learning science through engineering design has not changed some of my ideas about how the physical world works.	1	2	3	4	5
It is easy for me to explain how science concepts apply in everyday life through engineering design.	1	2	3	4	5
I am very comfortable designing engineering projects in science lessons.	1	2	3	4	5
I am confident in my ability to use engineering design skills to reason logically about the physical world.	1	2	3	4	5
Engineering design is NOT an effective tool for learning science.	1	2	3	4	5

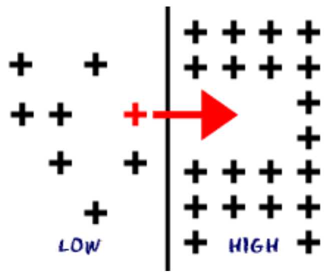
Resource B – Post Assessment

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?

Section B

6. What is engineering?

7. Describe the engineering design process. Use a diagram to illustrate your answer.

8. Is the engineering design process linear or cyclical? Explain your answer.

9. What is the difference between the scientific method and the engineering design process?

10. What is a design challenge in engineering?
11. What is a design solution in engineering?

12. What did you like most about the engineering design process?

13. How did the engineering design process help you learn more about the cell membrane and cell transport?

Section C

Please respond to each of the statements below by choosing the response that best reflects your views on engineering design. The response options are:
1=Strongly Disagree (SD) 2=Disagree (D) 3=Neutral (N) 4=Agree (A) 5=Strong Agree (SA)

Statements	SD (Strongly Disagree)	D (Disagree)	N (Neutral)	A (Agree)	SA (Strongly Agree)
I like engineering.	1	2	3	4	5
I like using engineering design to learn science.	1	2	3	4	5
Engineering challenges are fun.	1	2	3	4	5
I would rather do engineering than regular science.	1	2	3	4	5
I learn more science when using engineering design.	1	2	3	4	5
Learning science through engineering design has not changed some of my ideas about how the physical world works.	1	2	3	4	5
It is easy for me to explain how science concepts apply in everyday life through engineering design.	1	2	3	4	5
I am very comfortable designing engineering projects in science lessons.	1	2	3	4	5
I am confident in my ability to use engineering design skills to reason logically about the physical world.	1	2	3	4	5
Engineering design is NOT an effective tool for learning science.	1	2	3	4	5

Resource C – Engineering Design Packet – 8 pages (For Students)

Engineering Design Worksheet: Cell Membrane Model

Group Members:

____

Scenario & Design Challenge:

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:

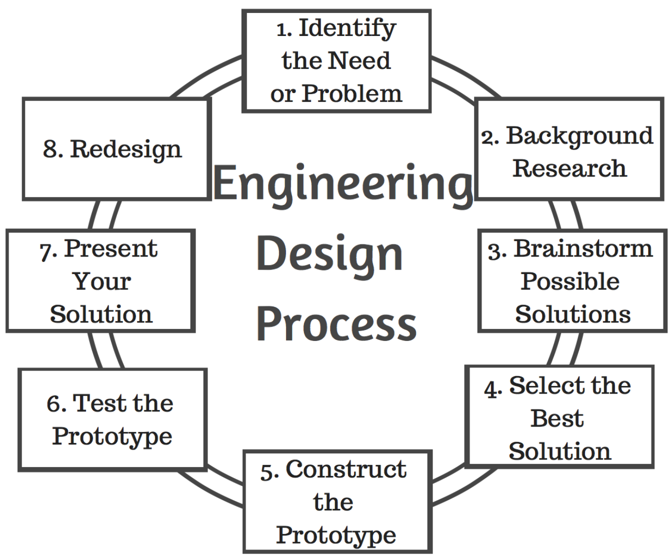
- Styrofoam ball - $5.00
- Tape (6”) - $ 3.00
- Cotton balls (x5) -$3.00
- Toothpicks (x10) - $ 2.00
- Drinking Straw - $1.00
- Coffee Stirrers (x5) – $2.00
- Rubber Band – $3.00
- Paper Clips (x 5) - $1.00
- Craft Foam (2”x4”) - $2.00
- String (6”) - $2.00
- Cheese cloth (2”x2”) - $1.00
- Pipe cleaner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

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 membrane, and release it.	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
Ability of membrane to pass materials • Sand (O_2/CO_2) • Water • pom-poms (glucose) • marbles (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	All team members participate, but not equally.	Not all team members participate; only one or two speak/participate	/3

	at least all contribute heavily to the presentation			
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	

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
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.

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.
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.

<table>
<tr><td>5. CONSTRUCT THE PROTOTYPE

(everyone must answer)</td><td>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.</td></tr>
<tr><td>Teacher Approval</td><td></td></tr>
<tr><td>6. TEST THE PROTOTYPE

(everyone must answer)</td><td>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?</td></tr>
<tr><td>7. PRESENT PROTOTYPE</td><td>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.</td></tr>
<tr><td>8. REDESIGN Does your cell membrane prototype meet requirements?

(everyone must answer)</td><td>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?

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)</td></tr>
</table>

Resource D – 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

8. 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:

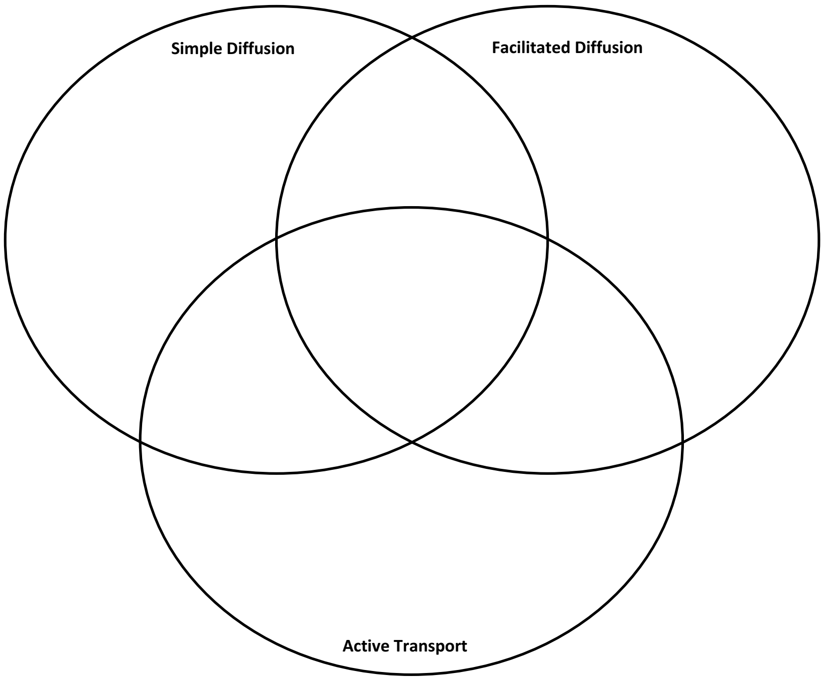
3. Differentiate between active transport and diffusion.

4. How did completing this project help with your understanding of how a cell membrane works in a cell?

5. 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.

6. Do you think you would have been able to complete this project easier if you were working alone? Explain...

Resource E: Venn Diagram



Resource F: Group Materials and Cost Outline Sheet

Group Materials and Cost outline

Group Members: ____

Material	Amount	Cost