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The Incorporation of and Engagement in Engineering Design in High School Biology

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The Framework for K-12 Science Education and the Next Generation Science Standards propose that students learn concepts and practices related to engineering as well as science. Currently the research surrounding how engineering practices through engineering design are implemented in the life sciences such as high school biology is limited. To explore how engineering design is included in a biology class, a case study was conducted in two high school biology classrooms. This qualitative case study examined how high school biology teachers incorporated an engineering design project into a science curricular unit and how high school biology students engaged in an engineering design project in biology class. The results show that while the intention of the engineering design project was to include science learning related to the biology unit, the project was treated as a practice independent of the science unit of study. Students were able to successfully engage in the engineering design project with differing results dependent upon the type of instruction given in the biology class.

KEYWORDS: Engineering design, Iterative, Biology, NGSS, Engagement, Incorporation

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M.E.P.

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CHAPTER I: INTRODUCTION

Reforms in science education intended to increase science performance in the United States have focused on integrating science, technology, engineering, and mathematics (STEM). In response to a need for updates in STEM education, the National Academy of Sciences chose to create a new set of standards for K-12 science education. According to Ruth, et al. (2019), equitable representation in the STEM fields is a national goal driving science and engineering education reform. Within the National Academy of Sciences, the National Research council (NRC, 2012) developed *A Framework for K-12 Science Education*. Released in 2010, it is the conceptual framework from which the Next Generation Science Standards (NGSS) were created. According to the NGSS Executive Summary, the standards "are rich in content and practice and arranged in a coherent manner across disciplines and grades" (2013, p. 1). Included in the *Framework* is the idea of science for all. Underlying the importance of this is the intention for the development of scientific literacy. All students, regardless of background or language of origin, should be able to apply the concepts and skills learned in science to decisions about personal and societal problems. What is absent from this integration of science and engineering is how engineering and engineering design is included in secondary science classrooms (Moore, et al., 2014).

The intention of the structure of the NGSS is to direct three dimensional learning. The intended instructional approach is for students to engage with integrated Science and Engineering Practices (SEPs), Crosscutting Concepts (CC), and Disciplinary Core Ideas (DCIs) in order to understand or make sense of phenomena. This integration illustrates the importance of engaging students in both science inquiry and engineering design. The goal is to better situate scientific inquiry into the authentic work of engineering (Hite, et al., 2020). The

NGSS are driven by the three dimensions and the relationship they have to each other. Lesson planning, learning, and assessment using the integration of the three dimensions provides opportunities to engage students at a deeper level in ways that allow them to contextualize learning within the real world (Custer, et al., 2018). This challenges teachers to plan curriculum that supports the connection of science learning to industry, business, and careers (Custer, et al., 2018).

Zeidler (2016) considers the ability to teach science using the NGSS a challenge for teachers because they are complex, and teachers' often hold limited understanding of the three dimensions. This complexity is imposed upon already complex demands of teaching in an actual classroom with a diverse student body. While it is argued that the three dimensions included in each NGSS performance expectation (PE) are important, the ability to weave all three together in a coherent way, that is meaningful to all student groups, is difficult (Pang, et al., 2014).

Within the *Framework* and the *Standards* there are two major goals for K-12 science education: "(1) educating all students in science and engineering and (2) providing the foundational knowledge for those who will become the scientists, engineers, technologists, and technicians of the future" (NRC, 2012, p. 10). The goal of the framework is to prepare all students to pursue STEM college degrees and careers and to be informed citizens (Januszyk et al., 2016). These goals have changed the focus of science education from memorizing content and practicing inquiry in isolation to building and applying science knowledge (Krajcik et al., 2014). Included in the standards is the integration of engineering practices into science instruction. According to Mentzer et al. (2015), the standards establish engineering as a fundamental part of science learning as students are expected to transfer science knowledge through the science and engineering practices. Engineering, as defined by the NRC, is "any engagement in a systematic practice of design to achieve solutions to particular human problems" (2012, p. 11). Meaningful STEM education includes using both engineering practices and content knowledge in problem-solving (Park, et al., 2018).

Significance of the Study

This qualitative case study sought to explore how engineering design was incorporated into the specific science learning environment of a high school Biology class. The study investigated how biology teachers planned for the incorporation of an engineering design project into a curricular unit of study driven by specific NGSS life science and engineering standards. This study also examined how high school biology students engaged in the planned engineering design project. The NGSS do not define how teachers should integrate science and engineering but instead provide recommendations such as attending to and prioritizing a range of criteria and constraints, breaking a problem into smaller parts, and assessing the impacts of solutions (Hite, et al., 2020). This creates an even more complex situation for science teachers to define what engineering is in relation to three-dimensional learning when planning lessons and curriculum. The body of research on engineering in a science classroom is small but growing. Research focusing on engineering design outside of science class focuses on engineering integration with other learning such as a study done by Wilson, Smith, and Householder (2014), which examined how technology teachers could use literacy skills to support the engineering design process. They examined the use of specific literacy practices within four stages of the engineering design process. Allen and Peterson (2019) examined how using a problem-based learning approach within the context of engineering based activities in a mathematics class could provide task authenticity and therefore increase mathematical learning. Findings from this study concluded that engagement in authentic engineering-related material allowed students to see the relevancy to the real world which led to increased learning of the included mathematical concepts. Now that this intended incorporation of engineering into science through the use of the NGSS is approaching its tenth year of intended use, further exploration of the specific use incorporation of and engagement in engineering in science is necessary. More research needs to be done focusing on how the integration of engineering into a science class supports learning science. For this reason, this study contributes evidence of the use of engineering design in biology through the following two research questions:

Research Questions

How does a high school biology teacher incorporate engineering design into their biology classroom?

How do high school students engage in an evidence-based iterative engineering design project in biology?

Limitations of the Study

This study was conducted with two educators from one high school. The researcher had a prior relationship with both of the teachers included in the study. One teacher in this study was not present in the classroom during the study and a substitute teacher was responsible for teaching during that time. Further limitations are explained in Chapter III.

Organization of the Study

The following qualitative case study was conducted with two high school Biology teachers teaching independently in their own classrooms at the same school. Each teacher instructed different groups of students in biology. The study explored how the two teachers planned and implemented the incorporation of an engineering design project within the biology curriculum and how high school students engaged in engineering design during the project. The following chapter provides a review of current research related to the incorporation of an engagement in engineering design in standards-based science. Following a review of the literature is a chapter describing the methods used to collect and analyze qualitative data during this case study. The findings specific the two research questions guiding the case study are organized into data collected and thematic findings in a separate chapter followed by a final conclusion chapter including implications and suggestions for further study.

CHAPTER II: LITERATURE REVIEW

This study drew on research from various education fields to explain biology teachers' and students' experience around the standards-based teaching of an engineering design project. This chapter focuses on the literature that guided the study. Because this study focused on the inclusion of an iterative engineering design project occurring in high school biology using the NGSS, the literature review begins with a brief explanation of standards-based science using the NGSS. The curricular unit created by the two teachers in this study included both science and engineering standards and therefore relevant research related to engineering in science has also been reviewed as a means of contextualizing the findings related to the incorporation of and engagement in engineering design in science. Within this contextualization is an exploration of how engineering design is selected for biology within a standards-based curriculum, how specifically the engineering design component is selected and implemented, and the science sensemaking required by the specific students engaged in engineering design in science. This review illustrates the thus far narrow approach to research related to the implementation of standards-based engineering design into high school science classes such as biology. The review of literature focused on the following two research questions.

Research Questions

How does a high school biology teacher incorporate engineering design into their biology classroom?

How do high school students engage in an evidence-based iterative engineering design project in biology?

Standards-based Science Using NGSS

Science and engineering intersect in a number of ways in the real-world. Understanding how the world works from a variety of perspectives, including from those of life and environmental sciences, contributes to the understanding of engineering (Hite, et al., 2020). In turn, understanding and participating in the practice of engineering should contribute to the understanding of science. This points to a process of integration of these perspectives into science education. The NGSS include engineering practices within the SEPs used in each science discipline; life, physical, Earth and space science. According to the National Science Teaching Association (NSTA), "the practices describe behaviors that scientists engage in as they investigate and build models and theories about the natural world and the key set of engineering practices that engineers use as they design and build models and systems" ("NGSS," n.d., para. 1). Relating back to the three-dimensional learning intent of the NGSS, engineering design should be used to design solutions to problems related to real-world phenomena. The *Framework* provides further explanation of how engineering practices should be integrated in a multidisciplinary way to support scientific problem-solving within a context of the real world. The *Framework* includes a specific section entitled Appendix I: Engineering Design that includes specific engineering-related PEs: (NGSS Lead States, 2013, p. 2)

> A. Defining and delimiting engineering problems involves stating the problem to be solved as clearly as possible in terms of criteria for success, and constraints or limits.
>
> B. Designing solutions to engineering problems begins with generating a number of different possible solutions, then evaluating potential solutions to see which ones best meet the criteria and constraints of the problem.
>
> C. Optimizing the design solution involves a process in which solutions are systematically tested and refined and the final design is improved by trading off less important features for those that are more important.

Following the intent of the *Framework*, the NGSS also include separate performance expectations for engineering design organized by a progression in grade level bands including 9-12 shown in Figure 2.1.

Figure 2.1

9-12 Grade Engineering Design PEs.

Students who demonstrate understanding can:

Performance Expectations

- Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants. HS-ETS1-1
  Clarification Statement and Assessment Boundary
- 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-ETS1-2
  Clarification Statement and Assessment Boundary
- 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. HS-ETS1-3
  Clarification Statement and Assessment Boundary
- Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem. HS-ETS1-4
  Clarification Statement and Assessment Boundary

Note. The NGSS engineering design performance expectations for grades 9-12. Reprinted from *NGSS Lead States*, 2013.

"Grades 9-12 Engineering design at the high school level engages students in complex problems that include issues of social and global significance" (NGSS Lead States, 2013, p. 5)

Fostering a relationship between engineering design and science inquiry to support the learning of a phenomenon relies on knowing the similarities and differences between the two. The NGSS require a pedagogical approach to create a common set of experiences using both scientific inquiry and engineering design in order for students to understand and demonstrate understanding of phenomena. Although the SEPs offer similar practices between science and engineering, there are generally different outcomes (Boesdorfer & Greenhalgh, 2014). Lederman et al, (2009), identified that "science inquiry extends beyond the mere development of process skills such as observing, inferring, classifying, predicting, measuring, questioning, interpreting, and analyzing data. Scientific inquiry includes the traditional science processes, but also refers to the combining of these processes with scientific knowledge, scientific reasoning and critical thinking to develop scientific knowledge" (p. 142). Harkema, et al. (2009), argued that the nature of scientific processes including the examination of cause-and-effect relationships in nature through asking questions and carrying out investigations and using the manipulation of variables to produce a desired outcome is a science model which is different from an engineering model. Scientists interpret data and construct explanations while engineers design solutions and troubleshoot design (Whitworth & Wheeler, 2017). But that is not to say there is no relationship between the two. "Engineering designs are informed by scientific knowledge and advances in science are made feasible by technology developed by engineers" (Whitworth & Wheeler, 2017, p. 26). At times, science investigations may already be engineering tasks that have not been explicitly distinguished as such. Such investigations would require the addition of the design loop process and specific engineering language to embrace the integration the NGSS is directing (Boesdorfer & Greenhalgh, 2014).

The use of a STEM approach to science and engineering learning supports student learning of both the natural and designed world. "One way to differentiate engineering from other problem solving endeavors is the use of scientific or mathematical knowledge to inform design" (Kruse, et al., 2017, p. 40). Although there is no single correct model for engineering design, there is a core set of ideas that guide the creation and implementation in the science classroom. Included in this is defining problems, design criteria and constraints, solution ideas and models, and solution testing and refinement (Custer, et al., 2018). The *Framework* and NGSS also recognize that the design process is a cyclical process in which students can engage in the steps multiple times (Whitworth & Wheeler, 2017). It is important to distinguish engineering design from simply making something or tinkering using trial and error. The design parameters and constraints and their relevance to the problem in the learning activity are key to creating effective engineering design instruction in science (Meyer, 2012). Students need to be able to apply what they know about science in the design process. A middle ground between a prescribed, cookbook-type lab with too many constraints and a totally open-ended project in which constraints can be overcome is where engineering design in a science classroom should lie (Kruse, et al., 2017).

In addition to the performance expectations specific to engineering design, included in the NGSS is *Appendix J* which indicates the goal of illustrating the interdependence and influence of science, engineering and technology, society, and the environment. This states core ideas about how all students should learn about the relationships among science, engineering, and technology, and how that impacts societal and environmental decisions. Each science discipline has specific performance expectations that include engineering design with this relationship in mind. The two specific performance expectations in the life sciences that include engineering practices are HS-LS2-7 in which students are expected to *design, evaluate, and refine a solution for reducing human impacts on the environment* and HS-LS4-6 in which students *create or revise a simulation to test solutions for mitigating adverse impacts of human activity on biodiversity* (NGSS Lead States, 2013).

Engineering in Science

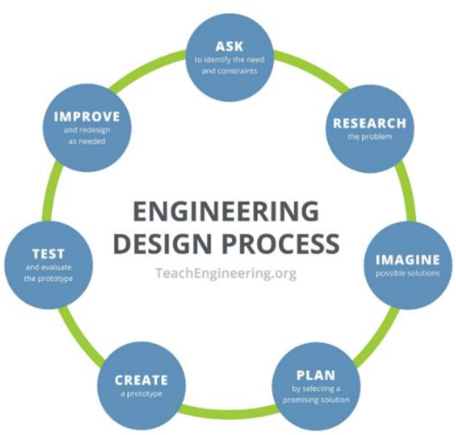
The two teachers in this study used a specific engineering design process as published in the TeachEngineering website (https://www.teachengineering.org/). This site which includes the engineering design process and curriculum was created by the University of Colorado Boulder through a National Science Foundation grant. The website defines the engineering design process as

> A series of steps that guide engineering teams as we solve problems. The design process is iterative, meaning that we repeat the steps as many times as needed, making improvements along the way as we learn from failure and uncover new design possibilities to arrive at great solutions. (University of Colorado Engineering, n. d., *engineering design process*)

A specific model of the engineering design process is included on the TeachEngineering website and was used by both teachers in their engineering design project used in this study. (Figure 2.2)

Figure 2.2

Engineering Design Process



In an examination of existing literature on engineering education, Cunningham and Kelly created a list of epistemic practices of engineering (2017). The purpose of these practices is to direct the development of materials, knowledge, and experiences to build engineering understanding. The development of these practices has implications for the development of engineering design processes and curriculum. The implication of listing specific epistemic practices of engineering was to address the limited ability of the NGSS to define this for teachers. This does not explicitly address how engineering supports science learning but may address a first step in the process to understand how to use specific engineering practices.

Attempts to study engineering in science have been made through the construction of updated observation protocols. One such protocol used in case studies was the Classroom Observation Protocol for Engineering Design (COPED). Wheeler, et al. (2018) observed that there were only two existing protocols aimed at engineering practices in K-12 classrooms, the Science and Engineering Classroom Learning Observation Protocol (SEcLO) and the Engineering Design-based Science Teaching Observation Protocol (EDSTOP). The focus of the SEcLO was on science and engineering vocabulary and behaviors, student frustration, and gender differences among these categories. The purpose of the EDSTOP is to code instances of specific components of engineering design in elementary classrooms. The authors used the advantages and limitations of both protocols to create the COPED as a way to study engineering design in science classrooms. The COPED included a pre-observation, observation, and post-observation section. While the focus of this protocol was on the engineering design process and engineering habits of mind, it did include a section on the integration of engineering design and science concepts within engineering lessons. The COPED defined a balanced approach to integrated design as "learning objectives weigh the engineering design and the core science ideas equally" (Wheeler, et al., 2019, p. 1299). It established levels in either the direction or being entirely engineering to being entirely science. This protocol did not focus on how students make sense of a science phenomenon.

A second observation instrument, the Reformed Teaching Observation Protocol (RTOP), developed by the Arizona Collaborative for Excellence in the Preparation of Teachers project was originally created to rate technology and engineering teachers' ability to teach science and technology and engineering within a preconstructed curriculum (Piburn & Sawada, 2000 as cited in Love, et al., 2017). The intention for its use was to rate or evaluate reformed science teaching. The RTOP contained three sections: lesson design and implementation, content, and classroom culture but separates the content and practices of science and the content and practices of technology and engineering in instruction (Love, et al., 2017). The RTOP was used in a case study by Singer, et al. (2016) to investigate the integration of engineering in high school STEM classrooms following professional development targeting use of a specific engineering design curriculum. In this study, the RTOP was used to indicate the level to which teachers were able to integrate science concepts and procedures into a cohesive engineering unit. This study found that teachers struggled to provide students opportunities to build science knowledge within the engineering design process and that science was presented in isolation. While this research is a good starting point, the RTOP did not address using engineering in a way that supports students' sense-making of a science phenomenon.

The most viable approach to connecting engineering and science concepts was the topic of a focus group meeting as part of the National science Foundation (NSF) Grant-funded Infuse project. The purpose of this focus meeting was to discuss how to best fit engineering into a science curriculum and what is the educational purpose of doing so. The participants agreed that an integrated or infused approach to engineering in science is more beneficial than a standalone approach. The consensus was that this integration should focus on design challenges that provide students with opportunities for scientific inquiry and application of science knowledge (Daugherty, 2012). This included more conversation about how science is taught and how to support science learning through an engineering project than in other research.

The amount of engineering included in NGSS does not mean it provides a thorough explanation of what it means to do engineering in science. Cunningham and Carlson (2014) explained that there is teacher confusion between engineering as a practice and engineering as an application of science as written in the NGSS. Their research pointed to elementary teacher's misrepresentation or interpretation of engineering practices in science.   This study however focused on whether or not the teacher participants are doing engineering right versus how engineering supports the student's learning of science. Chu, et al. (2019) developed an argument-driven engineering instructional model (ADE) for middle science in an effort to increase the quality of STEM education. The purpose of the ADE was to integrate the three dimensions of NGSS with engineering practices to solve a meaningful problem. This research targeted the development and measurement of engineering identity among the middle school students using ADE. The results from surveys conducted during the instructional process focused only on engineering recognition and interest and not on learning of science. Pleasants, Olsen, and Tank (2019) noted that at the elementary level, a common model of engineering instruction uses an engineering design challenge which included planning, prototyping, and testing to solve a problem presented to them. They identified that prior research points to teachers having difficulty connecting these design challenges to science. As a result, they developed a professional development experience for elementary teachers aimed at improving science and engineering instruction. The analysis of the data gathered through surveys focused on aspects of the nature of engineering but did not point to how science learning was supported through the engineering design project.

Being that the NGSS with the incorporation of engineering is still considered a more recent reform to science instruction, teachers have to navigate how this changes an existing science curriculum. A different study of 8th grade science teachers also using the ADE along with different STEM design challenges focused on teacher goal-conflicts with incorporating engineering design within science instruction. While the intention of the engineering integration was to prioritize science learning and engineering learning, by focusing on three-dimensional learning of the NGSS, the teachers still had concerns about student learning (Hutner, et al., 2022). According to Hutner, the design challenges used in this study included the integration of the three dimensions of the NGSS, construction, revision, and testing of evidence-based engineering design solutions, and peer critique and feedback throughout the challenge. The 8th grade teachers included in the study identified the amount of class time it takes to complete design challenges and potential lowered student performance on mandated science tests as conflicts with the importance of including engineering design in science class (Hutner, et al., 2022). The teachers were concerned with replacing existing science instruction with the STEM design challenges. The teachers felt that the pacing of their science classes differed significantly if the design challenges were completed as originally intended. This concern over the potential loss of science instructional time was closely related to the teachers' identified second goal-conflict of reduced student scores on mandated science tests. The teachers within this study varied in their levels of goal conflict resolution, but all the teachers modified both their existing science curriculum to include the STEM design challenges and also modified the design challenges to meet their perceived pacing and mandated testing goals. This variation of the preexisting science curriculum the teachers had used included teachers removing entire lessons not deemed as effective for meeting science learning goals to teachers to the use of lecture and note taking for some of the science topics included in the mandated tests. The modification of the STEM design Challenges and the ADE instructional framework in teachers' goal-conflict resolution varied from slight variations of the framework to cutting out entire stages of the instructional framework.

Guzey, et al. (2019), studied how a middle school life science teacher integrated engineering practices into science instruction over the course of three years. This case study was conducted in response to little specific research exploring how science teachers implement instruction integrating engineering and science concepts and practices. This study focused on the teacher's sequencing of content and practices and supporting student engineering talk through using engineering talk themselves during instruction. The study found that over the course of three years, the teacher modified the implementation of engineering integration from an add-on approach in which engineering was a stand-alone project in addition to learning science to the integration of engineering design into science learning. As the implementation changed, students gained more engineering knowledge and developed an interest in science and engineering. It can be concluded from this study that a strong connection between engineering and science concepts within classroom activities in which students learn and apply science through engineering design during instruction, supports student learning and interest in both areas.

Moore, et al. (2014) sought to develop a framework for quality K-12 engineering education. The purpose of the study was to identify ways in which teachers implemented engineering design in their classrooms as a means to create this framework. Due to the questioning of best methods in teaching engineering, the framework was intended to be an evaluation tool in STEM disciplines. Moore, et al.'s framework worked from three principles: 1) emphasis on engineering design; 2) incorporation of important and developmentally appropriate science and other STEM disciplines; and 3) the promotion of engineering habits of mind (2014). Included in the key indicators of quality engineering integration into science was the process of design including the problem, planning, and implementing, testing and evaluating, engineering thinking, applying science to this process, and teamwork.

Mathis, et al. (2018) stated that:

> engineering design, like the scientific process, is not one single process with a linear fixed set of steps to be followed by all engineers in all situations. Rather, engineering design is highly iterative and requires many decisions along the path to a solution. (p. 425)

According to Mathis, et al. (2018), engineering design has the potential to be a mechanism in which students engage in science content, but multiple factors influence whether the integration of engineering design does promote science learning. These factors are both student-focused such as prior familiarity with the content and teacher-focused such as providing steps to connect design and science. To shed more light on how successful integration of engineering design and science could occur, Mathis, et al. conducted a study of 7th grade science students doing an engineering design project using life science concepts previously covered in class (2018). The data used in the study was the students' use of science concepts either written or in conversation during the solution generation stage of the design. The study found that overall, students were able to use science concepts to defend their design ideas. It was noted that a specifically designed STEM integration curriculum can encourage students to make meaningful connections between engineering design and science with purposeful support of the application of science concepts to the design problem (Mathis, et al., 2018).

One study conducted by Sung and Kelley (2019) sought to explore how science students engaged in an engineering design task using problem-solving. This study included examining iterative design thinking within engineering design problem-solving. It was argued that patterns of design process aid students in the complexity of engineering design problems by providing successful problem-solving opportunities. Sung and Kelley argued that the iterative process of design activities "involve procedural patterns of cognitive repetition that vary by problem type and constraints" (2019, p. 284). The researchers used a design task in a fourth grade science class in which students participated as teams. Data was collected using student think-aloud activities specific to the design task and frequencies and durations of different cognitive strategies were investigated. Through sequential pattern analysis, iterative patterns related to designing in an engineering design task revealed that "when students generate ideas, designing is the central point of the entire process, often followed by drawing, predicting, or questioning" (Sung & Kelley, 2019, p. 299). The researchers used this outcome to make instructional suggestions for teachers to support problem-solving patterns within engineering design such as sketching and student assessment of designs.

In engineering design, argumentation or engaging in an argument from evidence is referred to as evidence-based decision-making (Siverling, et al., 2021). According to Gainsburg, et al., (2016, as cited in Silvering, et al., 2021), engineers use evidence-based decision-making in an iterative design process to prove a design works. The study conducted by Siverling et al. explored how middle school students engaged in evidence-based decision-making during an engineering design process as a means of providing ideas for how supports could be integrated into the process by teachers. Specific educational situations identified as teacher-prompted and student-directed were used as categories that prompted various levels of evidence-based decision-making use during engineering design. Because both teacher-prompted and student-directed situations led to evidence-based decisions about design ideas, this study argued that students have the ability to do this without needing teacher-directed prompts. Siverling et al. (2021) did also explain that teacher-prompting through conversation or through written documents further prompted students to use evidence-based decision-making and that asking students "why" and to reflect being even more beneficial at supporting this process.

Engineering Design in High School Biology

Research related to engineering practices in the life sciences is slim. Following the *Framework*, the purpose of engineering design in biology classes is to build foundational knowledge for engineering and biology concepts by investigating phenomena using science inquiry practices along with engineering practices. According to a current study in progress by Malone, et al., biology teachers lack experience and confidence with engineering design projects, leading to reduced incorporation of engineering design into life science classes (2017). Through an online professional development specifically supporting science modeling instruction, secondary biology teachers engaged in an engineering design project. The work in progress by this research team identified areas of weakness within engineering design understanding and engagement by the teachers. The current work did not include any connections to understanding engineering design and supporting learning of life science concepts and phenomena. Engineering design in the life sciences and particularly high school biology may surround biomedical engineering, synthetic biology, or ecological engineering. Common biomedical engineering activities focus on the creation of a prosthetic limb for a human such as *The Pirates* *of Prosthetics: Peg Legs and Hooks* from Teach Engineering's STEM Curriculum for k-12 (n.d.). In this activity, students would use the engineering design process to construct lower-leg prostheses. Chudler and Bergsman (2016) suggested that neural engineering should be used as a means of integrating engineering design into secondary biology. Neural engineering includes designing solutions for people with disabilities that affect the nervous system and Chudler and Bergsman argued that design challenges using this field leverage students' interests and everyday experiences (2016). They suggested the use of specific resources from a National Science Foundation-funded website called the Center for Sensorimotor Neural Engineering as a means to increase student interest in the field and because the topic aligns with both life and physical science concepts. Hite, et al. (2020) argued that design challenges related to Synthetic biology activities generally involve understanding the design and role of DNA and protein such as in the activity in Discovery Engineering in Biology Case Studies for Grades 6-12 called *Cutting It Close, Using CRISPR to Microedit the Genome* (2020). In this activity, students would use the discovery engineering process to propose gene editing solutions to global problems. According to Hite, et al., discovery engineering involves examining historical discoveries, materials, and data related to a phenomenon for which one will then propose new products or applications to solve problems (2020). Ecological engineering usually involves reducing impacts of invasive species or humans on particular habitats like Simpson and Whitworth's unit on global warming and pine beetles (2019). This type of engineering design includes a problem that needs a solution and specific criteria and constraints. Within the type of ecological engineering activity proposed by Simpson and Whitworth, students would engage in prior research and use previous scientific modeling to support the creation of a solution in which no physical prototype would be built (2019). Han et al. (2020) examined a science lesson intended for a STEM classroom using engineering, life science and mathematics. The lesson on biomimicry was designed using NGSS high school life science standards. Included within this lesson was an engineering design project where students would design and prototype fishing lures. Han et al. argued that teachers need well-structured lessons and instructional strategies in order to successfully integrate engineering into life science topics (2020). Regardless of the topic, engineering design projects in biology offer similar aspects to the general engineering design process used by other science disciplines. These types of activities promote problem-solving and decision-making skills, some requiring the students to build something while others using analysis of information to create a solution. While some engineering projects designed for the life sciences address either standard HS-LS2-7 in which students are expected to *design, evaluate, and refine a solution for reducing human impacts on the environment* or HS-LS4-6 in which students *create or revise a simulation to test solutions for mitigating adverse impacts of human activity on biodiversity*, other projects do not address either (NGSS Lead States, 2013). Some engineering projects intended for life science target NGSS engineering design standards such as HS-ETS1-3 in which students *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 within other life science performance expectations* (NGSS Lead States, 2013). This potentially increases the complexity of integrating engineering into life science units and the difficulty of understanding how this integration can be done successfully.

EQuIP Rubric

The use of existing frameworks in qualitative research can assist in the organization of the key concepts in the study in order to define the focus and direction for the study (Ravitch &

Carl, 2019). The EQuIP rubric can be used as a tool to help facilitate the explanation of variables in the real-world and as a first-step to align the research questions, data collection, and data analysis (Burkholder, et al., Eds., 2019). According to Reiser, et al. (2017), supporting students in multi-dimensional practices presents many challenges for teachers new to this approach. Achieving this requires more than just changing the alignment between standards, curriculum, and assessments. This requires helping teachers work on applying these reforms to their own classroom practice. Reiser (2013) emphasized three significant areas of teaching and learning explained in the *Framework* and NGSS. One is to help students continually work toward explanatory models or to figure out scientific ideas that explain how and why phenomena occur. The second is that students should use science and engineering practices to develop and apply these explanatory ideas. And the third is to have students building these ideas over time by revisiting building further on the ideas driven by questions arising from phenomena. Teachers can use specific supports to bring multidimensional learning into practice. A specific tool was created by Achieve, the nonprofit education association that helped facilitate the writing of the NGSS, to assist educators in creating and evaluating science units and lessons. The Educators Evaluating the Quality of Instructional Products (EQuIP) rubric provides criteria to evaluate science lessons and entire units designed for NGSS as seen in Figure 2.3.

Figure 2.3

NGSS EQuIP Rubric

I. NGSS 3D Design	II. NGSS Instructional Supports	III. Monitoring NGSS Student Progress
The lesson/unit is designed so students make sense of phenomena and/or design solutions to problems by engaging in student performances that integrate the three dimensions of the NGSS. A. **Explaining Phenomena/Designing Solutions:** Making sense of phenomena and/or designing solutions to a problem drive student learning. i. Student questions and prior experiences related to the phenomenon or problem motivate sense-making and/or problem solving. ii. The focus of the lesson is to support students in making sense of phenomena and/or designing solutions to problems. iii. When engineering is a learning focus, it is integrated with developing disciplinary core ideas from physical, life, and/or earth and space sciences. B. **Three Dimensions:** Builds understanding of multiple grade-appropriate elements of the science and engineering practices (SEPs), disciplinary core ideas (DCIs), and crosscutting concepts (CCCs) that are deliberately selected to aid student sense-making of phenomena and/or designing of solutions. i. Provides opportunities to *develop and use* specific elements of the SEP(s). ii. Provides opportunities to *develop and use* specific elements of the DCI(s). iii. Provides opportunities to *develop and use* specific elements of the CCC(s). C. **Integrating the Three Dimensions:** Student sense-making of phenomena and/or designing of solutions requires student performances that integrate elements of the SEPs, CCCs, and DCIs.	*The lesson/unit supports three-dimensional teaching and learning for ALL students by placing the lesson in a sequence of learning for all three dimensions and providing support for teachers to engage all students.* A. **Relevance and Authenticity:** Engages students in authentic and meaningful scenarios that reflect the practice of science and engineering as experienced in the real world. i. Students experience phenomena or design problems as directly as possible (firsthand or through media representations). ii. Includes suggestions for how to connect instruction to the students' home, neighborhood, community and/or culture as appropriate. iii. Provides opportunities for students to connect their explanation of a phenomenon and/or their design solution to a problem to questions from their own experience. B. **Student Ideas:** Provides opportunities for students to express, clarify, justify, interpret, and represent their ideas and to respond to peer and teacher feedback orally and/or in written form as appropriate. C. **Building Progressions:** Identifies and builds on students' prior learning <u>in all three dimensions</u>, including providing the following support to teachers: i. Explicitly identifying prior student learning expected for all three dimensions ii. Clearly explaining how the prior learning will be built upon D. **Scientific Accuracy:** Uses scientifically accurate and grade-appropriate scientific information, phenomena, and representations to support students' three-dimensional learning. E. **Differentiated Instruction:** Provides guidance for teachers to support differentiated instruction by including: i. Supportive ways to access instruction, including appropriate linguistic, visual, and kinesthetic engagement opportunities that are essential for effective science and engineering learning and particularly beneficial for multilingual learners and students with disabilities. ii. Extra support (e.g., phenomena, representations, tasks) for students who are struggling to meet the targeted expectations. iii. Extensions for students with high interest or who have already met the performance expectations to develop deeper understanding of the practices, disciplinary core ideas, and crosscutting concepts.	*The lesson/unit supports monitoring student progress in all three dimensions of the NGSS as students make sense of phenomena and/or design solutions to problems.* A. **Monitoring 3D student performances:** Elicits direct, observable evidence of three-dimensional learning; students are using practices with core ideas and crosscutting concepts to make sense of phenomena and/or to design solutions. B. **Formative:** Embeds formative assessment processes throughout that evaluate student learning to inform instruction. C. **Scoring guidance:** Includes aligned rubrics and scoring guidelines that provide guidance for interpreting student performance along the three dimensions to support teachers in (a) planning instruction and (b) providing ongoing feedback to students. D. **Unbiased tasks/items:** Assesses student proficiency using methods, vocabulary, representations, and examples that are accessible and unbiased for all students.

Note. EQuIP Rubric for Lessons & Units: Science (Version 3.1)

The three categories of the EQuIP rubric are aligned to the NGSS design, instructional supports, and monitoring student process. The language of the EQuIP rubric focuses on what scientists and engineers do such as answering questions, explaining phenomena, and solving problems (Ewing, 2015). The category of alignment to the NGSS focuses on using the integration of the three dimensions of the NGSS to support explaining phenomenon and or designing solutions. The instructional support category includes implementation of relevant and authentic scenarios that support student ideas about science in differentiated and scaffolded ways. The monitoring student process category focuses on using multiple ways to elicit evidence of three dimensional learning. Tools such as the NGSS EQuIP rubric are appropriate for this research as there is a strong focus in the EQuIP on explaining phenomena and designing solutions to problems (Ewing, 2015). Specifically, within the EQuIP is criteria I.A. titled *Making Sense of Phenomena or Designing Solutions to Problems* with the subcategories including sensemaking of a phenomenon and integration of disciplinary core ideas within engineering.

This sensemaking and designing necessitates the need for student engagement within the learning activities. According to Wardlow (2017), engaged students are actively constructing, analyzing, comparing, collaborating, creating, and reflecting upon information and ideas, a definition derived from the theory of constructivism. According to Ewing (2015) and O'Day (2016), there is a strong focus within the rubric on explaining phenomena and designing solutions as a means of supporting learning activities in which students have authentic engagement for a purpose. Also included in this focus is how teacher-generated materials support students to engage in the science and engineering practices during learning activities. According to O'Day (2016), use of the EQuIP rubric can pinpoint areas of growth within lessons for teachers such as "provide the students with an authentic situation or something in their experiences that will provide them with a purpose for sense making" (p. 29).

Sensemaking and Student Assets

> As science educators, we hope that our students will start to use scientific ideas and models that they learn in school independently as interpretive frameworks for making sense and explaining phenomena in the natural world and as a basis for innovative design. (Kapon, 2016, p. 165).

The use of science and engineering practices extends how inquiry is used in the classroom to support students to investigate and make sense of natural phenomena or the observable events the science knowledge can explain or predict. Instead of focusing on general knowledge, science phenomena allow students to figure out why or how something in the real world happens using general science ideas (NGSS Lead States, 2013). Using phenomena as the focus of instruction supports students' engagement in science practices to be able to explain or predict the phenomena.

According to Ancona (2012):

> Sensemaking, a term introduced by Karl Weick, refers to how we structure the unknown so as to be able to act in it. Sensemaking involves coming up with a plausible understanding—a map—of a shifting world; testing this map with others through data collection, action, and conversation; and then refining, or abandoning, the map depending on how credible it is. (p. 3)

Sense-making in science is a fairly new theoretical construct in science education research and consensus on its definition and scope is not widespread (Odden & Russ, 2019). Dewey's account of the sensemaking process included noticing something he didn't understand, coming up with ideas for why this would be, bringing in other knowledge, and proposing an explanation or solution (Odden & Russ, 2019). Other explanations of sensemaking include seeking meaning through construction of explanations across multiple representations and individuals (Cannady, et al., 2019). Schwarz, et al. (2017) explained sensemaking as a conceptual process in which a student wonders about, develops, tests, and refines ideas with others about the natural world. Kapon (2016) studied how two 7th grade science students explained the phenomenon of a shrinking bottle. Kapon conceptualized sensemaking as a process of evolution of self-explanations in which an explanation was generated, tacitly evaluated, and then reconstructed based on this evaluation (2016). This sensemaking includes learning and using scientific knowledge. Most research literature on scientific sensemaking focuses on the use of specific science practices. According to Cannady, et al., "scientific sensemaking requires cognitive engagement with science-related content as an activity of constructing explanations across representations, using methods generally aligned with the practices of science" (p. 2). Research also points to the relationship of how science knowledge is acquired through the use of the practices and how science knowledge is used in the practices. Ford (2012) studied how scientific sensemaking is constructed and supported through scientific argumentation. The premise of his study was that scientific sensemaking is developed socially through construction and critique during scientific practice. The study included two high school physics classes during a unit on ramp experiments. One class engaged in construction and critique through experimentation in groups with less-specific steps and instruction from the teacher. The second class received multiple types of instructions from the teacher on how to conduct the ramp experiments and what should occur during those experiments. Ford concluded that the class engaged in a sequence of construction and critique as groups of students better-supported the scientific process in sense-making versus the group being told what to do and what to expect (2012). Scientific sensemaking therefore includes the acquisition of science knowledge, the use of scientific and engineering practices, and the understanding of the nature of science to compose an explanation about a natural phenomenon. Schwarz, et al. (2017) explained that participation in sensemaking in the classroom includes sharing and evaluating ideas and then reaching consensus through working with others and that specific sensemaking in engineering includes having students explore how to create or manipulate a creation using design methods.

Haverly, et al. (2020) explored what classroom opportunities provided support for equitable sensemaking. They defined equitable sensemaking as "a co-construction of knowledge incorporating students' epistemic resources - including language practices, discursive forms, and cultural practices-not always traditionally legitimized in classroom spaces" (Haverly, et al., 2020, p. 64). Concerned with how teachers notice and navigate sensemaking moments in elementary school science, these researchers engaged in a case study to determine how this occurred in class discussions. It was determined that in order to support student sensemaking in science, one would need to make space for this sensemaking process. Haverly et al. argued that this process of making space for sensemaking meant there was a shift of epistemic authority from teacher to students so that the classroom became a space of shared epistemic authority (2020). In this study, epistemic authority was defined as knowledge and ways of knowing by one considered to be an expert in the classroom which is typically the teacher (Haverly, et al., 2020).

Included in Haverly, et al. 's idea of equitable sensemaking, in which there is an incorporation of students' resources, was the argument for focusing on student assets in science learning. Gravel, et al. (2021) explained that "all resources that learners bring to the learning context are considered useful for sensemaking and thus are productive in learning activities" (p. 279). Gravel, et al.'s research was intended to examine how shifting toward asset-based approaches to engineering learning could support engineering with youth of color. They analyzed how asset-based approaches to engineering instruction effected engineering learning in a community setting. These asset-based approaches were defined as "pedagogical, material, and social structures designed to value, center, and promote cultural and heterogenous ways of knowing and doing" (Gravel, et al., 2021, p. 277). From their case study, they found that how engineering design is imagined by an instructor affects the potential success of engineering learning and that using science-specific goals for inclusion of engineering design inhibits an asset-based approach to engagement in an engineering project.

Wilson-Lopez, et al. (2018) conducted a study based upon the idea that students whose families possess science capital are more inclined to want science-related careers than students with families that do not. Science capital was defined in the study as "social and cultural resources that support participation in science" (Wilson-Lopez, 2018, p. 246). The researchers explored how historically underrepresented youth used science capital in engineering projects. They were looking more specifically at how engineering projects could foster the use of specific students' funds of knowledge. This study used this term when "describing how implicit engineering practices can incorporate and legitimize local and cultural knowledge" (Wilson-Lopez, et al., 2018, p. 248). The students in this study were high school students participating in after-school clubs geared towards Latinaxs where they participated in engineering design projects related to problems within their communities. This study contributed evidence that engineering practices fostered the use of multiple forms of science capital. It was found that students, working in groups, used multiple forms of science capital to achieve specific goals within the engineering design project and that the use of resources by individual members of the student groups depended upon prior use of other science resources. Wilson-Lopez, et al. argued that engineering design can serve to validate students' diverse resources as valuable assets to doing science (2018). Specific examples of this included using existing science-related skills and knowledge, everyday experiences related to skills needed in engineering design, the use of digital technologies, and communication skills which were different among the students in the groups working together.

The description of asset-based approaches to learning can be broadened to include the belief the students' family, community, culture, language, and ways of knowing serve as intellectual resources which all contribute to the learning process which draws from the idea of funds of knowledge research (Celedón-Pattichis, et al., 2018). Schenkel, et al. (2021) argued that engineering design should leverage students' multiple funds of knowledge and introduced an engineering funds of knowledge framework which includes the aspects of using both technical and social expertise, include multiple design iterations, and connect to students' lives. Through the use of this framework, Schenkel, et al. encouraged teachers to "consider what expertise students might be able to tap into because of who they are and where they have grown up that could be useful in an engineering design challenge" (2021, p. 48). Through the identified aspect of using multiple design iterations within the funds of knowledge framework for engineering, it was argued that engaging in multiple iterations of the design process would allow students to bring new expertise into the process and that teachers should support this process in a design challenge. Schenkel, et al. continued to support the use of the engineering funds of knowledge framework by arguing that engineering design challenges that focus on real-life problems situated within local issues further allow students to use the wide-ranging expertise they bring to the classroom (2018).

CHAPTER III: METHODOLOGY

The purpose of this chapter is to describe in detail the methodology of the study, including the research questions, participants, data collection and analysis, and the limitations of the study.

This study investigated how engineering design occurred in a high school biology classroom through both the lens of the teacher and the students. Given that formal inclusion of engineering into science classrooms is entering its second decade with the *Framework for K-12 Science Education* and the NGSS, it is important to study the planning and enactment of engineering design. The inclusion of engineering into high school biology was initially met with concern and challenge (Guzey, et al., 2019). This chapter presents the research methods and study design used to investigate the following questions:

Research Questions

1) How does a high school biology teacher incorporate engineering design into their biology classroom?

2) How do high school students engage in an evidence-based iterative engineering design project in biology?

The manner by which a researcher frames the research questions is important as it generally determines the research methods in the study (Corbin & Strauss, 2015). Using Yin as a guide, the best approach to address these questions was an exploratory case study (2018). A single, exploratory case study was conducted to collect and analyze data from multiple sources. A case study allows an in-depth examination in a real-world context of the high school science classroom (Goodnough, 2010). “The qualitative stance involves focusing on the cultural, every day, and situated aspects of human thinking, learning, knowing, acting, and ways of understanding ourselves" (Brinkmann & Kvale, 2015, p. 15). This study followed this qualitative stance by examining both the teacher and the students in the classroom including the physical artifacts created by both. The purpose was to explore engineering design as a phenomenon situated within a science classroom. A classroom is not a controlled environment in which all students are constants that remain the same and therefore the "fluid, evolving, and dynamic nature of this approach" is appropriate for this study (Corbin & Strauss, 2015, p. 5).

The following description of the research context includes a description of the selection of the teacher participants and study location. In addition, the tools used in the study of the engineering design project are also described. Following the description of the research context, there is an introduction to the research design including a description of and rationale for the data sources that were collected and used. This chapter concludes by detailing the study's methods of analysis.

Participant Selection

According to Creswell (2013), a researcher should "select individuals and sites for study because they can purposefully inform an understanding of the research problem and central phenomenon of the study" (p. 156). The participants for this study were be selected based on the following criteria: 1) they were a high school (grades 9-12) biology teacher who was teaching at least two sections of Biology classes, 2) their class included at least one engineering project that was comprised of more than one class session, and 3) they were employed in a school district that adopted multi-dimensional science learning standards such as the NGSS or the participant self-identified as using similar standards for their own classroom. Table 3.1 describes the participants in terms of each criterion. The identification of a biology class was determined by the teachers in the school where they were employed. The identification of an engineering project was also determined by the participants chosen for this study. Two teachers were included in the study who worked together to plan an engineering design project. The inclusion of the two teachers and classes supported the exploration of both research questions.

An initial email was sent to two science educators to determine whether they identified as a biology teacher, use the NGSS or similar multi-dimensional standards, and had established the use of one or more engineering projects in a biology class. (See Appendix A)

Table 3.1

Criteria for Participant Selection

Participants	How identified as a biology teacher	Use of NGSS or similar multi-dimensional standards	Biology class(es) taught	Identification of an engineering project
teacher 1	Yes	NGSS	3	Two projects
teacher 2	Yes	NGSS	3	Two projects

The participants participated in an initial and follow-up interview (Appendix B), submitted all project materials including assessments to the researcher prior to engagement in the engineering project, and allowed observation of instruction with engagement by high school students in the project. In addition, the participants also were asked to submit student work with their assessment feedback to the students.

School Setting

The high school used in this study in which the teachers were employed, and the students attended has a total enrollment of 610 students. According to the school report card, the racial demographics of the student population consisted of 74% White, 4.9% Black, 6.9% Hispanic, and 7.9% Asian groups. The school reported 2.1% of the student body identified as low income. Students at this high school were required to take and pass two years of science in order to graduate and in 2021, 96% of students enrolled in college within twelve months of graduating. Information about the science classes offered were found on the school's website. All ninth grade students take biology as their first science class at this high school. An honors level of biology was not offered at this school. All students then take chemistry or accelerated chemistry their sophomore year. Students can take optional science electives in their Junior or Senior year which include advanced levels of biology, chemistry, physics, and environmental science.

Data Collection

A single, exploratory case study of an engineering design project in two biology classes occurred over the course of six weeks, during the 2021-2022 academic year. Important to the design of case studies is the defining of the case (Yin, 2018). According to Creswell (2013), a case is a bounded system that, in this case, was comprised of an engineering design project in a biological science learning environment. Multiple forms of data were gathered in order to support the exploration of the case. These included teacher unit plans and lesson plans, researcher observations of classroom implementation, collected student work related to the engineering design project, and video recorded initial and final interviews. The data were gathered between September 2021 and November 2021. The data sources are organized by corresponding research questions in Table 3.2.

Table 3.2

Data Sources for Research Question 1 and Research Question 2

Research Question	Data Sources
1 How does a high school biology teacher incorporate engineering in their biology classroom?	Initial and final interviews, teacher-generated unit plan, teacher-generated student document and accompanying research document, teacher-generated presentation slides, classroom observations
2 How do high school students engage in an evidence-based iterative engineering design project in Biology?	classroom observations, student work and presentations, feedback to students from teacher

Interviews

An interview is important evidence in qualitative research. The interview process provided the teacher's point of view and allowed the researcher to see their world (Brinkmann & Kvale, 2015). Two different semi-structured interview protocols for the participant teachers were designed for implementation and were scheduled across the instructional segment. The initial interview occurred approximately one month prior to the engineering project and both teachers were interviewed at different times. The final interview occurred several days after the completion of the project and only one teacher participated. The interviews were audio recorded and then transcribed. All teacher interviews were conducted using the online platform of Zoom and were recorded by the researcher. The researcher also took notes during each interview to assist in the semi-structured nature of the interview by supporting the creation of follow-up questions based upon interviewee responses. In the initial interview conducted prior to the engineering unit to be observed, the interview protocol provided information about each teacher's views of engineering and intended purpose of the engineering project (see Appendix B). The information in these questions reflected the different criteria of the NGSS EQuIP rubric (see Appendix C) as a means of focusing data collection for the research questions and its alignment is organized in Table 3.3.

Table 3.3

Initial Interview Questions

Interview Question	Criterion of NGSS EQuIP rubric
What do you think about engineering as a strategy to support learning in science?	II.A, I.B
How does engineering work in a life science classroom?	I.A, I.B
What challenges do you encounter when using engineering?	I.A, I.B
Do you value using engineering in your life science classroom?	I.A, I.B
How was the project selected/created?	I.A, I.B, II.A
What do students already know/can do related to engineering and the science phenomenon?	II.A, II.C
How are students assessed?	II.B
What are the next steps after assessment?	II.B

A second interview was conducted after the conclusion of the engineering project to support member-checking (Brinkmann & Kvale, 2015). The second interview examined whether the project met its intention by the classroom teacher and also targeted student assessment and the feedback the teacher provided to the students (see Appendix B). The final or post interview questions were also aligned to the NGSS EQuIP rubric to focus on data collection for the purpose of answering the research questions as seen in Table 3.4.

Table 3.4

Final Interview Questions

Interview Question	Criterion of NGSS EQuIP rubric
Was the project successful?	I.A, I.B
Were students successful?	I.C, II.A
How did you determine success (individual/collectively) – what criteria were used?	I.A, I.B, I.C, II.A
How did you determine what feedback was appropriate – how do students understand/use feedback – next steps?	II.A

Observation

Within the instructional segment, two classes were selected for daily observation across the duration of the engineering project. The researcher directly observed the instruction and student learning in the classroom during the entire engineering design project within the unit of study. Creswell (2013) suggested that a predesigned form to record information be used for observation in qualitative studies and therefore, conducting observations in this case study was supported by an observation protocol created by the researcher that emphasized the focus of the observations on the research questions. The observation protocol included the targeted and actual phenomenon of student engagement and recording of NGSS three-dimensional design and instructional support from the EQuIP rubric. Within the dimension of design, the protocol specifically targeted explaining phenomenon and/or designing solutions during specific time increments within the class. This allowed the researcher to record incidences of the use of student questions and prior experience within making sense of phenomenon and designing solutions. Within the dimension of instructional support, the protocol included the category of relevance and authenticity, opportunities for student ideas, and building progressions. Within the category of relevance and authenticity, the protocol allowed for the focus on students experiencing design problems directly with connection to student assets such as their own experiences, their community, school, or home. This was closely related to the category of building progressions in which observations of the use of student prior learning could be identified. The category of student ideas allowed for the documentation of students expressing or representing their own ideas and responding to peer and teacher feedback. Also included in the protocol were the steps of engineering design as identified by the teachers included in this study. The purpose of the steps of engineering design within the protocol was to allow the researcher to compare the design step intended by the teacher and student materials with the actual steps students were engaging in during class (see Appendix D). The EQuIP rubric consists of three dimensions of engineering design, instructional support, and monitoring progress. These dimensions focus on making sense of phenomenon and designing solutions. This checklist portion of the observation protocol allowed the researcher to organize observation into the areas of relevance and authenticity, student ideas, and building progressions organized under the category of NGSS instructional support for later analysis. In addition to the checklist, the observation protocol also included a section for field notes. This allowed the researcher to note important moments of engineering practice and science learning that will also have significance in the later analysis (Corbin & Strauss, 2015).

Physical Artifacts

To provide a broader lens for this study, as well as a better understanding of the study's context, data collection included additional artifacts (Yin, 2018). Data included the unit plan that was developed by the two participating teachers as well as teacher-created classroom materials and student artifacts such as the student's project document and final project presentations. These artifacts were critical in the constant comparison process and shed light on both how the teachers planned for the engineering design project and how the students engaged in the project.

The collection of artifacts for this study occurred before and after the observed engineering project in the science classrooms. Initially, the classroom teacher participant submitted to the researcher the teacher and student materials which included a unit plan, instructional materials, student activities and supports, and the project assessment. After the observed engineering project was completed, the two classroom teacher participants submitted student work and one submitted feedback given to the students by the teacher.

Data Analysis

The organization of data collected in this study as originating with either teacher or student allowed for analyses to inform each research question separately, but also supported the drawing of connections between the two research questions. The researcher analyzed data by teacher sources and student sources separately. The characteristics or intentions of planning and then teaching were observed as they occurred. As each source was examined, various categories of the EQuIP rubric were used in an initial coding process. Then similarities and differences in teacher plans and teaching and student actions and products were examined. Engaging in an initial deductive coding stage to include the teacher interviews, teacher unit plan and engineering activity materials, classroom observations, researcher notes, and student artifacts provided a focused lens to identify relevant data. This ensured structure and relevance from the beginning while enabling a closer inductive exploration later in the process through a hybrid coding approach (Linneberg & Korsgaard, 2019). That is, beginning coding with EQuIP criteria with the teacher interviews allowed for comparison and verification of the data through various data sources. For example, both teachers identified places in the student document where students would engage in a specific aspect of science or engineering during the initial interviews. The researcher was able to compare student work and classroom observations from that same day. This hybrid method of analysis created a broader lens through which the researcher could compare what each teacher was discussing during interviews with various other data sources such as the teacher-generated materials, student artifacts and classroom observations.

The process of deductive coding was first used in this study. This was appropriate due to the variety of data forms included (Saldaña, 2016). In the design of this case study, criteria from the EQuIP rubric were used in the creation of the interview and observation protocol as a way of helping to shape the data collection. This design allowed for data collection to reflect the intent of the research questions and therefore yielded analytic priorities (Yin, 2018). According to Yin, whether initial analysis codes are defined at the beginning of the case study or later, one's analysis should address the most significant aspect of the case study. The types of data collected were compared to each other and the beginning coding analysis tool of the EQuIP rubric. This allowed the researcher time to brainstorm possible meanings without jumping to conclusions (Corbin & Strauss, 2015). After analytic memoing from the interviews using the criteria of the EQuIP rubric, the process continued with the unit plan, the student document, classroom observations, and student work. This beginning coding process provided the starting point and allowed the researcher to compare parts of the teacher interviews with the other data collected, looking for similarities and differences (Saldaña, 2016). As the research process developed, so did the type of coding, which allowed the researcher to move toward answering the research questions (Linneberg & Korsgaard, 2019). Table 3.5 organizes the beginning coding data items and the criteria from the EQuIP rubric used in this initial analysis.

Table 3.5

Initial Coding Analysis

Data Collected	Initial Coding Analysis from EQuIP Rubric Criteria
Initial Interview Responses	I.A., I.B., I.C., II.A., II.B., III.A.
	Physical Artifacts
Teacher	I.A., I.B., I.C., II.A., II.B., III.A.
Student	II.A., II.B., III.A.
Observation Protocol	II.A., II.B., III.A.
Student Work and Feedback	I.A., I.B., I.C., II.A., II.B., III.A.
Final Interview Responses	I.A., I.B., I.C., II.A., II.B., III.A.

The first round of analysis was deductive coding using a framework that was drawn from the EQuIP rubric to identify a starting point of categories and patterns related to teaching an engineering design project. The EQuIP rubric (see Appendix D) is organized into three criteria which are *I. NGSS 3D design, II, NGSS instructional supports and III. monitoring NGSS student progress*. This initial framework was appropriate for coding as the classrooms observed for the study used NGSS for planning, instruction, and assessment. Within each of the three criteria, specific components such as explaining phenomena or designing solutions were included for analysis based upon each research question focus. For example, within the second criteria of NGSS instructional supports, the component of student ideas was included in this beginning coding as the engagement of students within an engineering design project was the focus of the second research question. The process of coding was iterative and over the period of a week, the researcher coded each area of data separately using this framework until 100% intra-rater agreement was achieved. The process of coding each piece of data separately using this framework began with the initial interviews. Analysis of the initial and final teacher interviews occurred in three iterative stages: a) transcription and coding; b) creating representations from the EQuIP rubric; and c) interpretation. The documents generated collaboratively by the two teachers in the study were examined critically because they reflect their perspective of classroom engineering design (Saldana, 2016). The classroom observations were then analyzed from the field notes within the observation protocol. The researcher coded the field notes and generated analytical memos around relevance and authenticity, student ideas, and building progressions from the EQuIP rubric. The process of memoing from the field notes allowed for a more in-depth and complex exploration of data (Corbin & Strauss, 2015). This process continued with the student documents and presentations and the final interview of one teacher. Interpretations of the data from this coding process was organized as evidence from each item in a table. This allowed the researcher to see patterns or themes and possible similarities and differences between teacher planning materials, classroom actions, and student products. Through analytic memo writing, reflection on the coding of this data served as an initial means of category generation (Saldaña, 2016). This initial process allowed for the codifying of data and supported the generation of themes or categories. For example, under the EQuIP criteria of NGSS design, the statement of "making sense of phenomena and/or designing solutions to a problem," is used multiple times. The researcher noticed a difference between the data related to sensemaking of a science phenomenon and designing a solution to a problem and split the first code into two categories for further analysis. Under the monitoring student progress criteria of the EQuIP rubric, the statement of "make sense of phenomena and/or to design solutions," is used. The data coded under this criterion was also further split between sensemaking of a science phenomenon and designing a solution as a means of reorganizing the data. The EQuIP criteria of NGSS instructional supports includes multiple subheadings related to student engagement related to student assets. Upon further analysis, the researcher found it appropriate to lump the data into a larger code of student assets to make the data more manageable. This reanalysis allowed the researcher to reexamine the initially coded data as a means of focusing the analysis for developing themes. According to Saldaña, "your first cycle codes are reorganized and reconfigured to eventually develop a smaller and more select list of broader categories, themes, concepts, and/or assumptions" (2016, p. 234). The researcher looked for emergent patterns across the interview responses, physical artifacts and observations based upon this and other initial analyses in a second coding process using the categories created from the initial deductive coding. The initial ideas about themes emerged and engagement in thematic analysis followed to support the development of trustworthy themes. Through extensive analytic memoing from multiple rounds of coding with the EQuIP criteria and further categorisation, themes emerged to better explain the data to address each research question. The difference in focus between the two research questions, one on teachers and the second on students, drove the ultimate process of generating different themes from the initial coding data. These themes combined examples of things found in the first cycle of analysis which, when woven together, began to provide further evidence of explanations of planning and engaging in engineering design (Rubin & Rubin, 2012, as cited in Saldaña, 2016, p. 200).

The responses to the initial interview questions were then recorded into the following themes through thematic analysis to provide meaning to the data (Saldaña, 2016).

The first research question addressing how a biology teacher incorporates engineering design into their class informed the generation of these specific themes found in Table 3.6 as a means to answer the question.

Table 3.6

Themes for Research Question 1

Themes	Descriptions
Planning to Incorporate Engineering in Biology	teacher planning of instructional strategies and supports for an engineering design project
Iterative Process of Engineering Design	teacher use of a design process in an engineering design project
Using student assets in learning	teacher selection of instructional strategies specific to students
Demonstration of student learning	teacher-planned assessment of engineering design and science concepts

The researcher then used those themes as criterion to describe what the evidence was and why it was evidence. The physical artifacts used by the teacher to support the teacher in instruction and the students in learning were also recorded using the themes. Similar to that of the initial interview questions, the researcher recorded what the material was, where it was found and why it was evidence of the particular criterion it is listed under. The field notes from the observation protocol were coded and the researcher generated analytical memos around standard integration, an iterative engineering design process, identifying and using student assets in learning, and the demonstration of student learning. The researcher transferred those comments into specific evidence of a particular theme and generated analytic memos around explanations for each. The field notes section of the observation protocol allowed for additional descriptions of what was observed to be included in the analysis as appropriate.

A similar process was used to provide data analysis specific to the second research question which focused on how high school students engaged in an evidence-based iterative engineering design project in biology. The initial process of coding continued as described above. Observations of student engagement in the engineering design project during class and student presentations given in class on the last day of the project were captured within the classroom observation protocol and analyzed. The visual slides created by the students for their presentations and the feedback given by one teacher to the students in one class on their presentations were also coded. From this initial deductive coding process, analytic memos were generated around what the students were doing each day of the project in class, what information they presented about their design project on the last day of the project, and the written feedback provided to the students after the completion of the project and the presentation. After data organization into the criteria of the EQuIP rubric, the researcher observed a similar categorization process as with the first research question. This included the specific focus on the student engagement in engineering design and the splitting of the student evidence of learning between sensemaking of a science phenomenon and designing solutions. Observations of students during the project were then recorded into those categories through further analytic memoing. From this hybrid coding approach, a thematic analysis continued to provide meaning to the data (Saldaña, 2016). As the second research question addresses how students engaged in an interactive engineering design project in biology class, the themes found in Table 3.7 are specific to learning and performance during the project.

Table 3.7

Themes for Research Question 2

Themes	Descriptions
Iterative Process of Engineering Design	student use of an engineering design process
Evidence of Student Learning of Engineering Design	student demonstration of use of an engineering design process
Evidence of Student Learning of Biology	student demonstration of knowledge of science concepts related to unit

The researcher then used those themes to describe what the evidence was and why it was evidence. Observations of students in each class each on each day included in the observation protocol, were then written as an analytic memo explaining how students engaged in the iterative process of engineering design. The observation of students on the last day of the project in each class included in the observation protocol illustrated only the presentations of their projects. Observations of what students included in the presentations were written as an analytic memo explaining how students engaged in the iterative process of engineering design and demonstrated evidence of learning related to the engineering design project. Similar to that of the process outlined above for the first research question, the researcher recorded the physical artifacts of the visual slide presentations created by the students and the written feedback provided by one teacher to one class after the presentations and why it was evidence of the particular criterion it was listed under. The responses to the final interview which focused on the student product, teacher feedback and success of the engineering project was recorded into the appropriate themes with the researcher explaining why it is evidence of this.

Validity

According to Yin (2018) construct validity includes using multiple sources of evidence. Within this research study, there was triangulation of data. The researcher collected data from interviews, classroom observations and examination of instructional materials and student work. The collection and coding of this data was based upon the published instructional tool of the NGSS EQuIP rubric. This was an appropriate tool to provide an initial framework for analysis as it was created to provide criteria to measure NGSS integration including engineering in lessons and units. This allowed for examination of the unique characteristics of a science classroom. The use of existing frameworks and literature was a first-step in establishing the validity of the observation protocol (Shah, et al., 2018). The validity of the observation protocol, created by the researcher using an existing evaluation instrument, was first established through refinement and analysis. The researcher designed an initial observation protocol and field tested this protocol with initial classroom observations prior to beginning the research. Revisions were made based upon this field test, with the researcher further testing the protocol through the use of online teaching and learning videos.

Limitations

One limitation of this research is that it included one case study with two participants. The participants and researcher have known each other prior to the case study. A second limitation was that one teacher participant was not present in the classroom during the engineering design project and a substitute teacher was present instead. This classroom teacher also did not participate in a final interview after the project was completed. Having an observation protocol and a specific coding strategy through the use of the NGSS EQuIP rubric addressed these limitations. The use of theory helped generate implications from the data and analysis of the case study. This worked to explain why things occur versus just being a description of what was happening. The evidence in a case study could "shed empirical light on some theoretical concepts or principles" (Yin, 2018, p. 38). This occurred from the original intention or plan of the case study and from what was learned through the process. Analytic generalizations based on theoretical concepts results in stronger research (Yin, 2018). The use of codes and coding once data had been collected was a way to progress toward a theory (Saldaña, 2016). This research however, instead led to a summative statement or key assertion rather than theory development (Saldaña, 2016).

Interpretation

Interpretation of the data for research question one was especially dependent on the initial interview data, and the other sources of data were essential to support those interpretations. Interpretation of the data for research question two was especially dependent on the classroom observation data, and the other sources of data also were essential to support those interpretations. As a result of using a hybrid method of analysis, beginning with deductive coding using criteria from the EQuIP rubric followed by the creating of more specific categories and then thematic analysis, the researcher arrived at several interesting interpretations. Detailed analyses of these interpretations are discussed further in the chapter that follows. The interpretations and analysis have important implications for how engineering design is included in a high school science classroom and how science teachers integrate an iterative engineering design project into a standards-based Biology classroom to promote student engagement. Further, analysis suggests the need to consider improving the ways in which teachers plan and implement engineering design projects to engage students in both science and engineering.

This chapter presented the research methodology and study design that guided this qualitative case study. Chapter IV first provides a brief summary of the findings based on the coding and analysis of the data as described in this methods chapter. Chapter IV then presents the findings related to the first research question focused on the teachers. This includes the teachers' planning and intentions of the engineering design project. The next section of chapter IV presents the findings related to the second research question which is focused on students. This includes how the two different classes of students engage in the engineering design project planned by the teachers. Chapter V, the final chapter, presents a discussion that aims to bring the findings together to highlight the significance and contribution of this study as it relates to science teachers implementing engineering design.

CHAPTER IV: FINDINGS

Introduction

The purpose of this study was to examine the nature of inclusion of engineering in a secondary Biology setting and address the following research questions:

How does a high school biology teacher incorporate engineering design into their biology classroom?

How do high school students engage in an evidence-based iterative engineering design project in biology?

Guided by the case study methodology described in chapter III, the study setting, and nature of the data is first described in this chapter. These descriptions are then followed by sections focused on each research question, separately. The complete data collection timeline, including initial interviews, material collection, classroom observation, and post interview occurred between September 20, 2021, and November 2, 2021. This study occurred in a high school with an enrollment of 610 students within two different teachers' biology classrooms where students were engaged in an engineering design cycle (Table 4.1). A fourth period freshman biology class consisting of 25 students, 12 of which had permission to participate in the study, and a fifth period freshman biology class consisting of 27 students, of which 25 had permission to participate in the study were included in the data collection.

Table 4.1

Criteria for Participant Selection

Participants	How identified as a biology teacher	Use of NGSS or similar multi-dimensional standards	Biology class(es) taught	Identification of an engineering project
Bob	degree in BTE and taught HS biology classes for 4 years	Uses NGSS	3 classes per day	water filtration device
Tom	degree in BTE and taught HS biology classes for 14 years	Uses NGSS	3 classes per day	water filtration device

Note: Biology Teacher Education (BTE), high school (HS)

Two teachers employed at the same high school, one with four years of teaching experience (Tom) and the other with fourteen years of teaching experience (Bob) were identified for this study. Both were teaching freshman Biology at the time of this study. Both teachers planned the biology unit called Biodiversity and Human Impact on Biodiversity, selected the accompanying Next Generation Science Standards (NGSS) performance expectations, and created the engineering design project collaboratively. The unit identified three NGSS performance expectations along with the accompanying multiple dimensions aligned to the performance expectations listed and acceptable evidence of student performance within the standards.

The unit sequence began with a case study on the water quality of a river intended to introduce the connection between water quality and biodiversity and the engineering design project in which students would design and build a water filtration device. According to the unit plan, students then demonstrated their understanding of the relationship between water quality and biodiversity through a similar case study on algal blooms in a river. Students were required to complete a claim, evidence, and reasoning scenario using the specific claim identified by the teacher of "water pollution, specifically runoff from farms that includes nitrogen and phosphorus, causes algae blooms which reduce biodiversity." Students were given two possible solutions to the algae blooms and were required to explain the solution they chose and provide their reasoning for the choice of solution. From here, the students began a six-day engineering design project in which they developed specific types of water filters based upon the type of water pollution present in a sample of water. The data sources represent the teacher planning and instruction and the student engagement in the engineering design project. Table 4.2 identifies the data utilized in the development of this case study.

Table 4.2

Overview of Data Sources

Teacher

Interview Responses (2 for Tom and 1 for Bob)
Classroom Observations
Teacher-Generated Materials
    Unit Plan
    Student Document
    Research Guide
    Teacher Slides
    Presentation Rubric

Student
Classroom Observations Student Document Student Presentation Slides

The first research question focused on what the teachers did both in planning and in the implementation of the engineering design project. The teacher-focused data were explored and included the interviews, materials, classroom observations, and teachers' feedback on the student assessment. Through examination of the interview responses, teacher materials, and observations, several themes emerged surrounding the use of an engineering design project in a biology class. First, how did an engineering design project fit into a unit of study in a high school Biology class? As the school used standards-based curriculum and assessment, the researcher examined which specific standards from the unit plan were included in the engineering design project and their relationship to the unit and the other unit standards included. As this was identified as an engineering design project, the examination of how the process of engineering design was incorporated was important to addressing the research questions.

An important aspect of engineering design is how students engage in the process of sensemaking of a phenomenon or designing solutions reflective of the assets they bring to the process (NRC, 2012). Student engagement in sensemaking within engineering design can make their thinking visible (NGSS Lead States, 2013). However, teachers attended to specific things in the learning materials and interviews that were less evident or missing from the classroom observations and student work. The focus of multiple NGSS performance expectations in planning became disconnected from the instruction and assessment of students. While the connection between water quality and biodiversity was explicit in prior unit activities, this connection was less meaningful in the student's engineering design of water filters. The teachers emphasized use of evidence in engineering design both in interviews and student documents, but students' use of evidence in design varied. Therefore, the second research question focused on the student's engagement in the engineering design activity and examined the student work created and classroom observations during the engineering design project including the student presentations which were the final assessment of the project. The findings associated with each research question are discussed in the following separate sections.

Tom and Bob

There were two teachers included in this case study.   Bob with 14 years of teaching experience and Tom with four years of teaching experience. Both teachers taught freshman biology at the same school at the time of this study. All freshmen took biology and no leveled (i.e., honors) biology course was offered. According to the school report card provided by the state the school resides in, 96% of the students enrolled in college within 12 months of graduating high school in 2021. Both Tom and Bob described their previous knowledge and experience of engineering design as limited. According to Tom, there were limited experiences with engineering design in college, with the expectation of a scholarship program in which college students developed engineering design lessons for middle school students. At the time of the study, Tom was a student in a master's degree program and pursuing a "technology-based route with part of a class that had mini-lessons on engineering design." Bob stated that,

> When I went through college, NGSS wasn't really a thing yet. I've done a lot of my own kind of training, I guess, and my coworkers are a little better trained in NGSS and having them come in was helpful to me because I was already investigating moving to standards-based grading around NGSS. We've also been to NSTA (National Science Teachers Association) conferences a couple of times, but even the presentations I've been to haven't been specifically on engineering. (Bob, initial interview)

The two teachers co-planned and implemented the same student activity using the same unit guide, the same teacher materials, and the same rubric for assessment. From Bob's initial interview, previous experience with engineering design teaching in environmental science was identified, but neither teacher had taught this specific engineering design project in a biology class previously. According to Tom,

> I came up with bits and pieces (of the engineering design project), so like the concept, I kind of came up with the scenario but stole the engineering process from [Bob]. So [Bob] has done this filtering water project in environmental science class and we do a creek ecology project (in biology class) and have been wanting to do an extension off of it with engineering. (Tom, initial interview)

Bob explained a previous project done in biology in the years prior to the year of this study.

> We did this part in homeostasis and we gave them (the students) a project where they had to design gloves in that we had an arctic researcher came in and talked about his research in the arctic and we like connected that to the cold and how they had to be able to thread a needle with certain gloves. So, our kids engineered that but during that process they had to put their hands in cold water, just their fingertips and that's how they were testing it though threading a needle normally and then when their hands are cold how can they thread a needle and now with the engineered gloves to thread a needle. When we had a couple kids start passing out in multiple classes for keeping their fingers in water for a minute, we were like maybe this engineering project, we shouldn't be doing. (Bob, initial interview)

Bob and Tom chose to participate in this study because of their belief that engineering design is not just a standards-based teaching requirement but is a beneficial part of teaching biology. When asked what they thought of engineering design as a strategy for science, both believed it was a worthy strategy to use. Tom explained engineering design as "a big strategy for getting students used to being hands-on in the classroom, that is not always easy to do with other strategies in science." Bob explained engineering design as a strategy in science as "a huge advantage because they're (the students) going to go through the scientific process to determine if what they engineered is successful or not, so they have this question and they do research and they build their structure or whatever it is, and they have to test it." Both teachers elaborated about how this strategy engages learning related to engineering and engineering design used outside of the classroom. According to Tom,

> this is a really easy way for students to see how it's (engineering design) going to work outside of the classroom in real life and it's something that I think a lot of kids don't get a lot of practice with or introduction to, and it's a field that we need more diverse backgrounds of students going into, so I think it is important to introduce it to different groups of students. (Tom, initial interview)

Bob explained that,

it (engineering design) is very valuable because we are always talking about how you have to do research and you have to test and that test has to be confirmed by multiple different scientists in different ways and so they're (the students) going through that process when they do the engineering design. (Bob, initial interview)

The Interviews

The researcher coded the initial interviews in a process of initial coding as a means of giving a holistic view of the intentions of the teacher regarding the purpose and process of the engineering project. Both teachers participated in an initial interview, but only Bob completed a final interview at the completion of the unit. This interview occurred after the engineering project was taught and student performance was assessed. Both the initial and final interview questions were created using the specific sections of the EQuIP rubric, which drove the responses in such a way that the following four themes that emerged are reflective of the framing of the EQuIP rubric:

- planning to incorporate engineering in Biology
- the iterative process of engineering design
- using student assets in learning
- the demonstration of student learning

These themes were used as a lens to frame the case and each are discussed in the later sections using data collected during the study.

The Unit-Biodiversity and Human Impact on Biodiversity.

The unit entitled biodiversity and human impact on biodiversity was co-created by Bob and Tom. It was constructed into a unit plan as a document shared by both teachers as a guide to the teaching of this unit. The unit plan was provided to the researcher during both initial interviews and included an outline of the unit in table form which included the standards, student performances, a river water pollution case study, a second river case study labeled as an assessment and the water filter engineering design project. The unit plan's NGSS performance expectations, and student-framed standards are shown in Figure 4.1.

Figure 4.1

The Unit Plan's Next Generation Science Standards Performance Expectations

NGSS PEs **HS-LS2-2.** Use mathematical representations to support and revise explanations based on evidence about factors affecting biodiversity and populations in ecosystems of different scales. **HS-LS2-7**. Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity. **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 **Student-Framed Standards** **Biodiversity-** I can use mathematical representations to support and revise explanations based on evidence about factors affecting biodiversity and populations in ecosystems of different scales. **Global Challenge-** I can analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants. (Engineering)

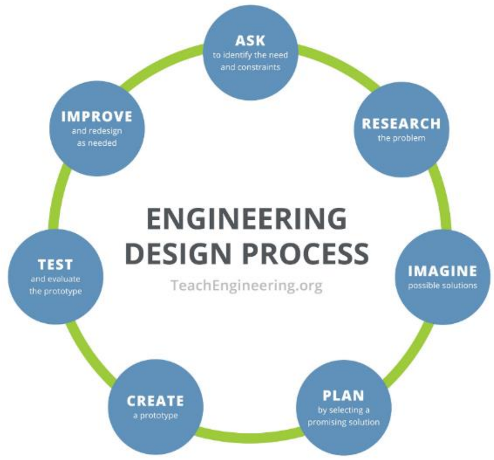
Within the NGSS website used by teachers, there are evidence statements for each performance expectation which provides a teacher with additional details as to what a student should know or be able to do (NGSS Lead States, 2013). There was a category included by the teachers within the unit plan called assessment strategies. This section identified the NGSS evidence statements for both the HS-LS2-2 and the HS-ETS1-1 performance expectations. Evidence statements for performance expectation of HS-LS2-7 were not included in the unit plan. The unit plan concluded with a sequence of activities for each day in the unit with the first three days being a river case study and the last six days being the water filter engineering design project. The unit plan did not delineate which evidence statements or standards applied to each activity.

The Student Document and Accompanying Teacher Presentation Slides.

The student document used for the duration of the engineering design project was in the form of an electronic Google Doc (see Appendix E). It began with an introductory scenario which explained the global need for clean water: *you work at a water filtration plant, and your team has been tasked with coming up with a new water filtration system that could be used in areas of the world that don't have access to clean water or solutions*. This introduction also identified more specific requirements of the problem students were to address in the project: *your filter will need to be made of basic items that are cheap and affordable as many of the areas do not have access to expensive items. You will also have limited time to make the filtration device as it is of the utmost importance that people get access to the filtration device as soon as possible.* This introduction also set up the need for research to be done by the students: *all (water) samples will have organic material and plastic pollution. However, you will need to research the body of water to determine one other prevalent pollutant*. This document included a visual for the engineering design process found in Figure 4.2.

Figure 4.2

Engineering Design Process



The document described how students would work through a series of steps in a group or as a team to design a successful filtration system. It identified specific roles students would choose which dictated the specific responsibilities of the student both during the process and in the final presentation. Those student roles are identified in Figure 4.3.

Figure 4.3

Student Roles in Engineering Design Project

Role: Description	Name of Student
Member 1: Project Manager: This person will be the head communicator for the group. They will be responsible for identifying criteria and constraints. They will also be responsible for making sure that all criteria are met for the prototype.	
Member 2: Design Tech: This person should be artistic and detail oriented as they will be responsible for overseeing the design or blueprint of the filtration system prototype.	
Member 3: Engineer: This person will be responsible for overseeing the building of the actual prototype.	
Member 4: Scientist: This person will be responsible for overseeing the testing of the prototype. They will record the effectiveness of the prototype and identify areas to improve.	

The student document was then organized into a series of steps following the given engineering design process. These steps were:

1. write problem trying to solve
2. research: students are given water to represent a specific area and use given research guide to identify type of pollution present in water and how to test for this pollution in classroom
3. imagine and plan: identify criteria and constraints specific to body of water and filtration systems (info found in research)

4. available materials for filtration device: cost analysis and place for drawing/model of design annotated with item name and purpose
5. build prototype filtration device
6. do initial test of water according to research pollutants / students pour water through prototype and test water again for same pollutants
7. written explanation of what was successful and what needs to be improved - reference test results, draw a new design with improvements - annotate design and highlight improvements
8. final presentation: explanation of requirements of presentation and rubric

Included in step 2 research, was an accompanying research guide for students to use. The sections of research and required information were color-coded according to the different student roles identified in the main student document and found in Figure 3. This research guide provided the students with teacher-selected websites targeting human impacts on water quality around the world, the health and environmental effects of poor water quality, how to create water filters, and materials used in water filters to filter specific pollutants (see Appendix F).

The accompanying teacher-created presentation slides were a series of slides labeled by day of the project. The intention of the slides was to supplement the instruction occurring each day of the engineering design project and to focus students' attention on specific tasks (see Appendix G).

Classroom Observations of the Teachers

While the teacher-generated materials were the same for both classes (Bob and Tom), the implementation of the project was different in each class as was the use of the teacher-generated materials. The classroom observations of each day of the project in both classes revealed these differences. In Tom's fourth hour class, there was a substitute teacher, Sara, who taught the entire engineering project. Bob taught fifth hour Biology each day of the engineering design project.

Tom's fourth hour Biology class began day one of the engineering project with Sara, the substitute teacher introducing the project to the students and then showing the video about inventing toys that was found on the fourth slide of the teacher-created presentation slides using the classroom overhead projector. In Tom's fourth hour classroom, the student desks were already arranged into groups of four with students having predetermined assigned seats. Sara the substitute teacher then assigned each group of four students to a specific type of water which was found in large buckets on the floor along one wall of the classroom. Sara then projected the student document and read the document to the students. The students were then prompted to assign themselves a role within the group using the descriptions on the student document.

The students in Bob's fifth hour Biology class were first shown examples of the different types of water sitting on a lab table and then shown the materials to be used in the water filters sitting on another lab table. Students were then prompted to read the student document to themselves and were given time to do this. Bob then asked the class what the problem was that they were going to solve, and a student identified clean drinking water. Bob pointed out to students that they would be evaluating and revising in the project before they would be designing. Bob then read both NGSS performance expectations included in the engineering design project and the project responsibilities by day using the teacher-created presentation slides. Bob then instructed students to read the descriptions of the specific roles in each group and to discuss with the rest of the group which student would take each role. Bob's classroom was also arranged with student desks grouped into fours and the students had a seating arrangement determined prior to the engineering design project.

Both Sara in fourth hour and Bob in fifth hour projected the accompanying student research guide found in step two of the student document and asked students to open the same document on their own laptops. Sara pointed out that the research guide is divided by the individual student roles within the group whereas Bob read each section of the research guide, explained what type of information was found in the websites listed and identified using the color-coding which role was responsible for which question and websites included in the document. Before the end of class, Bob defined the term constraints and explained that the materials provided in the classroom were an example of this.

On the second day of the project in both Tom's fourth hour, with Sara the substitute teacher and Bob's fifth hour classrooms, the class began with the day two teacher-created presentation slide on the overhead projector. Sara in the fourth hour class used the slide to identify what tasks of the project and the project document needed to be completed in class that day, which was through part three, design. This included beginning initial water testing and creating a water filter design and cost analysis. In Bob's fifth hour class, there was a teacher-led class introduction to the standard listed on the teacher-created presentation day two slide. Bob then defined both the term criteria and the term constraints for the class and then asked for students to say what the specific criteria of the project were. One student responded, "to create clean water by making a water filter." Bob then asked the students for examples of specific constraints in the project and different students responded with "the materials you gave us, how much money we can spend, and how much time you give us to make the filter." Bob then used the projector to show the student document identifying the parts of the engineering process in the document that needed to be completed in class that day. Bob organized this by identifying what group role was responsible for each step. When speaking about the scientists doing the initial water tests, Bob explained that the test or tests they were completing were determined by identifying specific pollutants in the water in the research the students had completed the previous day and that additional tests were not needed. Bob also reminded the students to complete the initial test results in the data table found in step six of the student document.

On day three of the project in both Tom's fourth hour class taught by Sara and Bob's fifth hour class, all student groups were gathering materials and working to build a prototype of the water filter they designed the previous day. Sara did not use any type of whole class instruction during day three but did provide answers to student questions about the project. Bob began day three by projecting the student document and reminding students of what should have been completed during class in the days prior. Bob then prompted students to step five design and step six test in the student document. Bob explained that the materials were all found on one lab table and that students needed to follow their design and cost analysis from step four of the student document to build their water filter. Bob reminded students that some water tests would need to have been started on the current day such as the coliform bacteria test which took two days for accurate results. The last prompt Bob gave the students was "you are following the design using specific parameters and using problem-solving skills as you attempt to make a physical model of the designs you created yesterday."

Day four of the project in both Bob and Tom's classes focused on redesigning the water filters. Sara in Tom's class used the day four slide from the teacher-created presentation to explain that the scientist should be water testing and the groups should be revising their physical models, and then provided no further direct instruction for the rest of the class period. Bob again used the student document to explain to students that they should have been completing step seven improve by testing and redesigning their water filters. Bob reminded students that "with each redesign, your group should add the materials to the design picture and add the cost to the cost analysis." Bob announced that the scientists in each group would complete their second water tests and that the testing table in the student document should have been completed by the end of the class period. This included the coliform tests even for those groups that did not have two days to run the test as was needed. Bob then showed the students the rubric for the presentations found at the end of the student document as a guide to point out what information should have been included in the presentation slides and communicated in the presentations.

Day five in both Bob and Tom's classes focused on creating a presentation of the engineering process of the water filters by the groups of students. Sara in Tom's fourth hour class read the day five slide from the teacher-created presentation to the class which stated: "each group member should work on their specific part of the presentation- please reference color coded rubric." Sara read the color-coded rubric for the presentation found at the end of the student document to the students. Sara prompted the students in Tom's class to use the rubric, so they understood what they were responsible for in the presentation. In addition to showing the students the color-coded presentation rubric, Bob also projected the color-coded rubric for the presentation for the students in fifth hour Biology. Bob reminded students to use data from their water tests and research to justify their revisions and to support their water filter designs. Bob asked the students to look specifically at question number three in step seven improve in the student document which asked: "How would you change the design to include the improvements? Draw a new design with the improvements. Remember to annotate the design to include labels of the materials utilized, what they filter, and specifically highlight the improvements in this new design." Bob stated that this was not a trial and error process and that students should go back to the researching portion of the project and that they could also do additional research from other sources in order to be able to go beyond the specific constraints given in the classroom project. Bob stated that the students were "allowed to reduce constraints in their discussion for the presentation."

Day six, which was the last day of the water filter engineering design project in both classrooms consisted of student group presentations. Sara in Tom's fourth hour class did not complete the presentation rubric to provide feedback to the students and did not ask the students any clarifying questions. Bob used the presentation rubric to provide feedback to each group. The rubric included the following criteria to provide categories of feedback:

- Defining the problem
- Criteria and constraints
- Developing engineering solutions
- Prototyping
- Testing and evaluating
- Revising (see Appendix E)

The feedback provided to students is presented in a table later in this chapter.

The following section explains how data from the sources were used in the emerged themes to answer the research question. As a result of the initial coding of the interview responses, several themes emerged and have been described. The teachers began by planning for engineering design in Biology considering how the biology and the iterative process of engineering design would be included. The teachers chose the curricular unit on biodiversity and human impacts on biodiversity as the unit to include an engineering design project. The expertise or assets of the students were considered as the students in freshman Biology classes varied in their educational and community backgrounds and prior experiences. The demonstration of student learning of both Biology and engineering design was addressed in the interviews, teacher-generated materials, classroom observations and teacher feedback to students. Similar to that of the interview responses, the teacher-generated materials and classroom observations of teaching will also be analyzed using the same themes. This will allow the researcher to look for patterns within the incorporation of an engineering design project. Evidence for each theme is presented in the following order: teacher interviews, teacher-generated materials, and classroom observations of the teacher.

Research Question 1: How does a high school Biology teacher incorporate engineering in their biology classroom?

Planning to Incorporate Engineering in Biology

The teachers began by planning a unit on biodiversity and human impact on biodiversity which would include an engineering design project. The theme of planning to incorporate engineering in Biology was addressed through the unit title and biological content related to biodiversity and human impacts and also addressed the included NGSS as this was a standards-based unit of study.

The unit began with a case study of the water quality of a specific river in the state where the school resides and included the involvement of humans and water pollution. Solutions to the pollution in the river were framed in the case study that the students engaged in and was followed by their identification of evidence for how river water quality was related to biodiversity. Students were responsible for explaining their reasoning for the selection of a specific solution to the water quality issue. Bob, in the initial interview, explained that the engineering design project of creating a water filter is a new phenomenon that the students would engage with but that it fits within the biodiversity unit. Both Bob and Tom explained that the engineering design project is based on an existing creek ecology project done prior to the biodiversity unit where students use a research question about invertebrates to determine water quality of a local creek and to study types of water pollution and the effects. The intention of the teachers was that this should lead to the idea of drinking water issues and the need to build a filtration device.

> I would say we treat it (engineering design project) as a separate unit now in our like we have several units on ecology and within those units, the theme, they do a big lab report and look at biodiversity around the creek and its water quality and so although I would not say this specific thing is tied into biodiversity, from going from the creek project to learning about population sizes and then they did like a little mini unit that focused around water pollution and biodiversity, just kind of flowed into okay now let's look at water pollution and its impact on human populations. (Bob, final interview)

Bob explained how the two teachers came to a consensus on the order of learning activities in the biodiversity unit.

> Originally I think we thought about going straight from the creek ecology project where we've identified the water health in the creek, let's go straight into how do humans impact it and build this filtration system well, then I think we thought, maybe it would be better to get how we measure populations, we wanted to hit that biodiversity standard ahead of time and do that around the human impacts around water pollution, so it just seemed to work out better in the place that it was. (Bob, final interview)

The teachers described that they started with specific performance expectations as they developed the unit because the high school in this study uses both standards-based curriculum and standards-based grading in the classrooms. The identification of those performance expectations was important as the consistency of these standards throughout the teaching, student engagement, and assessment was questionable. In addition to HS-LS2-2, a biodiversity standard, the project also included HS-LS2-7, *design and evaluate a solution to human impacts*. According to Bob, there are many standards included in their biology curriculum including all of the life science standards, some of the Earth science standards and then engineering standards. Bob elaborated that there was “not time to meet all the standards in one year.” Both Bob and Tom referenced parts of standard HS-ETS1-1, *analyze a global challenge*, as being assessed in the engineering design project.

> I don't know that I would say it (engineering design project) ties perfectly to like a content standard for populations. I just felt like within things that we've been studying about water quality, it just kind of flowed and was a nice way to cap that off because now we go into a completely new direction and we started macromolecules. (Bob, final interview)

In response to the HS-LS2-7, *design a solution* and HS-ETS1-1, *analyze a global challenge* NGSS performance expectations, Bob described

> I mean, I think it targets that standard because they're designing right, but I actually put it in as an engineering standard. I actually put it in as analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and that's the standard that I actually scored it (assessment). (Bob, final interview)

Tom also stated that HS-ETS1-1, *analyze a global challenge* is assessed in the engineering design project. Because both Bob and Tom agreed that the high school engineering design standard included in the unit is assessed as a result of the engineering design project, engineering design itself is a main theme and discussed specifically in the next section.

In the student document, (see Appendix E) the introductory scenario introduced students to a global need for clean water for humans to use. This appeared to be related to the creek ecology project referenced in the interviews as done prior to this unit but not included in the unit plan and also the three-day case study of water pollution in a river which was included in the biodiversity unit plan. There was an attached research guide for students to use when they completed Step 2 Research, on the student document (see Appendix F). The first two websites provided from the World Health Organization (WHO) and the Centers for Disease Control (CDC) provided facts related to global human access to clean water. The WHO website (https://www.who.int/news-room/fact-sheets/detail/drinking-water) provided to students on the research guide provided facts and statistics related to humans and their access to clean water. Students could also find information about human health concerns related to contaminated water along with economic challenges of providing clean water. The CDC website (https://www.cdc.gov/healthywater/global/wash_statistics.html#:~:text=An%20estimated%202.2%20billion%20people,access%20to%20basic%20handwashing%20facilities) also provided statistics and health concerns related to access to clean water. Also included in the additional research guide were two websites for each different type of water or the region where the types of water samples represent. These websites included information about the occurrence of pollutants in the water and impacts of the pollutants in the water to humans and other living things. For example, the first website listed for the sample of water representing Uganda (https://borgenproject.org/the-issue-of-water-quality-in-uganda/) explains that Uganda is a country in Africa and the types of water pollution and the number of people affected by it. The second website for Uganda on the research guide (https://ugandabiodiversityfund.org/why-uganda-should-ban-plastic-bags/#:~:text=Currently%2C%20it%27s%20estimated%20that%20at,them%20are%20disposed%20of%20irresponsibly.&text=Plastic%20bags%20are%20also%20the,causing%20threats%20to%20aquatic%20life) was specific to Ugandan water pollution by plastics. Students were tasked with answering specific questions according to their individual role within the group. The questions related to biodiversity and human impacts were:

- What is the significance of clean drinking water?
- What are the consequences if drinking water is unclean?
- Criteria: What is the type of pollution in the water and how did it get there, what's the source?
- Describe the location
- How is the pollutant harmful?
- How did it affect the water quality?

The accompanying teacher-created presentation slide (see Appendix G) used on the first day of the project in which the students researched items related to biodiversity and human impacts included both standard HS-LS2-7, *design a solution* and standard HS-ETS1-1, *analyze a global challenge*. The display of the standard HS-LS2-7, *design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity* attended to the idea of including biodiversity and human impacts within the engineering design project. This same standard was repeated on three additional slides in the teacher-created presentation, but no additional slide content applied to the biodiversity unit.

The standard of design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity (HS-LS2-7) was represented in the research guide provided to students. While none of the descriptions of the four student roles included on the student document specifically identified responsibilities outside of engineering design, all students were provided the research guide. The assigned project manager of each group was responsible for determining the significance of clean drinking water and the consequences of unclean drinking water. It can be concluded that humans have somehow impacted the condition of drinking water in the world and that this has had an impact on the environment and biodiversity. The project manager also was to identify the type of pollution in the water, the source of the pollution, and characteristics of the area the water sample represents to determine why a cheap water filter is needed. It can be concluded that these research requirements would lead to the identification of human activities causing the pollution and evaluating a solution according to the economic status of the location the water sample represented.

Similarly, the rubric at the end of the student document had the purpose to be used to assess the final student presentation. The project manager was responsible for the following criteria as listed under defining the problem in the rubric created by both teachers: T*he essential problem calling for an engineering solution was clearly described, giving reasons for its significance and consequences if it remains unsolved. Clearly identifies the overall problem. Clearly describes significance if it remains unsolved and research is referenced.* This reinforced the idea that at least one member of each student group needed to attend to specific parts of the standard by determining human activities contributed to the water pollution problem and that the problem has environmental and biodiversity implications. The student assigned as the design tech was tasked with researching and identifying methods to get rid of the pollutants in the water. This addressed the designing of a solution portion of the standard. The student assigned as the engineer was to then research and identify whether those methods were affordable and if they would be successful. This addressed the evaluating a solution portion of the standard. Using the student presentation rubric found on the student document, the responsibilities of the design tech, the engineer, and the student assigned as the scientist attended to portions of designing, evaluating, and revising a solution. For example, the design tech was to present information for the following: *Multiple filtration methods were considered. These solutions were refined using research and experimentation. A leading solution was selected using the criteria identified earlier.* This presentation criteria used specific terms found in the standard. The engineer was to present the group's prototype, explaining how it followed the group's design. The engineer was also responsible for presenting specific research the group used to suggest effective changes to or revisions of the original prototype. Essentially the engineer was to attend to both the design and revision of a solution. The scientist of the group was responsible for presenting their evaluation of the prototype in the following way; "The prototype was tested to determine the effectiveness of the proposed solution. Test results were analyzed and used to identify strengths and weaknesses of the proposed solution in terms of project constraints and criteria." The scientist was to attend to the evaluation of a solution.

The standard of *analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants* (HS-ETS1-1), was specifically listed in the rubric for the student presentation included in the student document. The introductory scenario on the student document provided students with information about global human access to clean water which would be considered a major global challenge. In step two of the student document where students were to research specific aspects of the identified problem, there was some analysis of a global challenge. Students were to identify the pollutants in the water samples according to a global region which should have also pointed out possible societal needs and wants related to the specific region. Also identified where possible solutions through information about existing water filters and the materials used to filter water pollutants. In step three of the student document called imagine or plan, students were given the definitions of criteria and constraints and were to identify both for their design. By also providing fees for materials used in the design and a specific maximum final cost of the design, the document supported specific constraints of a solution which should also be tied to the societal needs and wants as written in the standard.

Most of the evidence from the classroom observations of teaching was directly related to the evidence in the teacher-generated materials, but there were differences between the two classes. On the first day of the engineering design project, Bob displayed and read aloud the two NGSS performance expectations labeled as standards on the teacher-created presentation slide. As stated earlier, the first was, HS-LS2-7, *design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity,* and the second was *analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants* (HS-ETS1-1). These were two of the three standards included in the planning of the unit. In similar fashion, on day two of the project, Bob both displayed and read aloud the NGSS performance expectation listed on the teacher-created presentation side which was HS-ETS1-1, *analyze a global challenge*. There was no observable attending to the biology of the planned unit such as a connection to biodiversity within the problem or relating the project to the previous activities such as the river case study within the unit of study. Feedback given for the student presentations by Bob attended to Biology only in a limited manner. Some feedback included comments about the specific identification of the problem related to the identification of specific pollutants in the water samples, how the pollutant got into the water supply, and the pollutants' health impacts on humans. Biodiversity could be implied but was not explicit in these statements.

Iterative Process of Engineering Design

The engineering design process used by the two teachers in the project was from the Teach Engineering website (https://www.teachengineering.org/) and was illustrated in Figure 4.2. According to this website, an interactive design process means that one can repeat the steps of the design process as needed to make improvements (University of Colorado Engineering, n. d.). Moore, et al. (2014) explained that "solving engineering problems is an iterative process involving preparing, planning, and evaluating the solution at each stage including the redesign and improvement of current designs" (p. 5).

During Tom's initial interview, the student document was shared on the screen and the steps of engineering design were illustrated. According to Bob in the initial interview, this was the first time the two teachers used this specific project and Bob described it as adding to an existing project. The two teachers developed the engineering design project together by taking pieces from other projects such as the water filtration project that Bob had done in the environmental science class previously. During the initial interview, Bob shared the student document which included an engineering design model to illustrate that the "importance is this is something they (the students) can build and test." According to Tom, the project was both a good hands-on project for students and it also introduces engineering design to a different group of students as all Biology students would be doing this project. Tom elaborated that they want to introduce new concepts through engineering design to promote student interest in the subject so they will want to continue to learn science and engineering.

Both teachers also identified areas of concern with incorporating engineering design in their classes related to planning a project. Bob shared that, "this (engineering design project) takes the teacher lots of time to set up and requires specific materials and supplies and time to acquire those. Also finding research articles for students to use and the time to do that." Tom stated that the "teacher has to have lots of background knowledge to help students. Supplies and materials need to be accessible to a high school classroom."

> [I]f I could have more time in a semester I would love to spend an extra three days, where they (the students) spend another day after testing on researching and another day designing and then another day retesting to see if their alternatives basically worked and so, in an ideal world, where we don't have so many time constraints, I feel like in so many standards to get through, I would spend the extra time on that. (Tom, final interview)

Other issues surrounding the teaching of an engineering design project emerged. One was the number of students doing a project and how one would manage this. According to Bob there were, "specific student roles within the project and you have a large number of students divided into seven groups all doing engineering design." Tom described that there was a "need to keep it simple in order to support seven groups of students all doing different things at different times." Bob also identified that

> most of them (the students) had the components to filter their two pollutants, but then they were filtering other things that were not part of their scenario like I had quite a few

> kids running the coliform bacteria test, even though they didn't identify animal waste or human waste in their waste in their water. (Bob, initial interview)

When addressing what students are able to do during an engineering design project, Bob reflected on the overall experience of the students within the unit,

> Students enjoy doing a hands-on project and ecology is an easier subject in Biology for an engineering design project…the overall goal was for students to identify criteria and constraints for that problem and then create something…and the kids were able to reflect, which is probably the most important component, right, to reflect on what was working and what was not working and doing outside research to investigate. (Bob, final interview)

Tom elaborated on this reflection portion of the project in the initial interview.

> I think that reflection piece is probably the most valuable just as a life skill like if you fail at something that doesn't mean you failed right, as long as you can learn from it and so them understanding that piece, I think is important. (Tom, initial interview)

In the final interview, Bob thought the students had a good understanding of what they were doing and why they were doing it. And even though Bob thought the students understood the research behind their selected solution, Bob did state that "a lot of their research always tends to be a little vague, even with specific guided questions to support doing and using research." Bob described in the final interview that students were able to outline the problem, not just in their area (where water was from), but also worldwide. They used websites from the Centers for Disease Control (CDC) and the World Health Organization (WHO) about why drinking water is a problem worldwide and the different diseases that occur in different countries. Students were successful in identifying their two pollutants in the water samples that they had to filter correctly and identifying that there were components in their filtration system that were actually going to filter those pollutants.

The student document included a diagram of an engineering design process chosen by the two teachers and the steps in the document followed the order of the engineering design steps displayed. The student document addressed the process of engineering design by following the steps in the diagram. Each step in the document included more specific information or tasks students should accomplish before moving on to the next step. For example, within the research guide included in step 2: research on the student document, there were four websites specific to designing a water filtration device:

- https://www.itsoverflowing.com/diy-water-filter/
- https://www.h2odistributors.com/pages/info/how-to-make-a-water-filter.asp
- https://www.waterfilteradvisor.com/how-to-make-charcoal-sand-water-purifier-at-home-science-project-diy/
- https://tappwater.co/en/what-activated-carbon-filters-remove/

Each website provided options for the structure of a water filter as well as possible materials to be included in a filter and the material's purpose in filtering water. Additional websites were provided for different types of water contaminants explaining how specific components of a water filtration device filters a specific pollutant. An example of this was nitrogen which had the following website listed (https://tappwater.co/en/what-activated-carbon-filters-remove/) which explained how carbon filters or charcoal filters work. The research guide included specific questions related to the design:

- What are methods that could be used in order to get rid of this pollutant?
- Are they affordable?

- How successful will this method be?
- What would the cost of this method be?

Step 3: imagine and plan began with the following explanation, "Now that you have researched the body of water and effective filtration systems. Take a minute to identify criteria and constraints. Criteria is what the design needs to be able to do, the purpose. Be specific to your body of water, via your research, what should you be filtering. Constraints are limitations to the design." Next in the student document was a table for students to identify or list criteria and constraints separately. After this, a list of materials available to create a water filter was listed along with the price for each item. The document identified a maximum allowable price for the filter as $15.

On day two of the teacher-created presentation slide entitled Monday, the standard HS-ETS1-1, *analyze a global challenge* was listed as a support of the project process. Students were prompted to complete specific tasks according to their assigned role within the group. For example, all students were to discuss the criteria and constraints of the project while the project manager was to get the research checked by the teacher, the scientist was to get the types of water pollution in the sample identified and to begin initial water testing. The designer and engineer were to work on the creation of a design of a water filter along with a cost analysis. This was a support of the students' use of multiple steps of the engineering design process, specifically the research, identification of criteria and constraints and designing a solution to the given problem specific to the samples of water given.

Step 6: Test your Prototype, of the student document explained to students that initial and final water tests need to be conducted. In addition to this, a chart of safe levels of pH, nitrogen, phosphorus, and coliform bacteria was included so students could compare their results to determine if their prototype was successful. The document included a data table for students to complete before and after using the filtration system prototyped which included smell and appearance of the water, the identified pollutants, and the amount of the pollutant found using water testing materials provided by the teacher.

The day three and day four (Tuesday and Wednesday) slides in the teacher-created presentation included both the HS-LS2-7, *design a solution* and HS-ETS1-1, *analyze a global challenge* standards. On the day three slide, students were prompted to have their design of a water filtration device checked by the teacher and to build the prototype of the filter. It was also noted that students should complete the initial water tests of their sample of water. On the day four slide, students were prompted to use their prototype to filter their water sample, complete the final water tests, and to complete analysis questions. It is assumed the analysis questions are those found in step seven of the document.

Step 7: improve included specific questions for students to answer related to how their prototype was successful and how their prototype could be improved, promoting them to use the testing results to justify the success and the improvement. The final question in this section was "How would you change the design to include the improvements? Draw a new design with the improvements. Remember to annotate the design to include labels of the materials utilized, what they filter, and specifically highlight the improvements in this new design." This encouraged students to engage in this step of the engineering design process even though, as stated in the initial interviews, time in class was not specifically given to return to previous steps in the design process in order to make multiple prototypes or revisions to an existing prototype.

Again, the use of the teacher-generated materials varied between the two classes which was directly related to the attention to and support of the iterative engineering design process. On the first day of the project, Sara showed a YouTube video about how toys are invented as a means to introduce the idea of the engineering design process versus the creation of something correct and fully functional. Bob prompted the students to read the student document themselves on the first day of the project and then asked the students to communicate the problem to be solved in their own words. Bob pointed out to the students that they would need to evaluate and revise their ideas before designing a prototype in the project. On the second day of the project, Sara defined the term constraints and listed the specific project constraints for the students. Bob defined both the term criteria and the term constraint for the students but asked the students to communicate both the criteria and constraints for the project themselves in a whole-class discussion. On the third day of the project, Sara did not provide whole-class support or discussion of the project or engineering design while Bob read the prototyping and water testing steps of the student document to the entire class. Bob also prompted students to create a prototype of their design using problem-solving strategies. On the fourth day of the project, Sara used the teacher-generated presentation slide to explain to the entire class to complete water testing and prototype revisions that day whereas Bob displayed step seven from the student document to prompt students to test and redesign their water filter prototypes. Bob reminded the whole class to modify their designs and recalculate their cost analysis with each redesign of their prototype. The last day of the project before the presentations, Sara prompted the students to work on their presentations and provided no further support for this process. Bob reminded the entire class to use data from the water tests to justify the revisions made to the prototypes. Bob also pointed out that students needed to draw a new design which included the needed materials, cost of the materials, and an explanation of what each material is used for. Bob stated that revising a prototype is not a trial and error process and that students should conduct additional research to support their revisions especially if the students are working outside of the original constraints and using additional materials not available in the classroom. The feedback provided to students by Bob specific to engineering design targeted correct identifications of criteria and constraints and using research and data to justify designs and revisions.

Using Student Assets in Learning

The teachers also identified both areas of concern and opportunity within teaching an engineering design project. Areas of concern included the students' prior experiences with engineering design before high school and their ability to successfully complete the project within the time given. Using student assets in the planning and implementation of an engineering design project is defined as addressing and leveraging student's funds of knowledge in a sensemaking process (Schenkel, et al., 2021). Interview responses reflected the teachers' use of the various forms of student expertise and practice developed over time. Scharz, et al. (2017) explain sensemaking as a conceptual process in which a student wonders about, develops, tests, and refines ideas with others about the natural world. This sensemaking includes learning and using scientific knowledge. Sensemaking in engineering includes having students explore how to create or manipulate a creation using design methods (Scharz et al., 2017).

Bob indicated in the initial interview that the biology students have varied but little prior experience with engineering design, but they have prior experience in Biology class with science practices. Both Bob and Tom provided the students with prior science activities with safety and homeostasis. At the beginning of the school year, students participated in a safety lab and later an investigation of homeostasis using human body systems. Bob pointed out that the students value and enjoy hands-on projects. *"[T]*his is the first engineering design project in the high school for these students. They all come from different middle school backgrounds and we're not sure of prior experiences with engineering design" (Tom, initial interview). Briefly addressing the specific water filtration engineering design project, Tom shared that "students have learned in real life that so many places have a need for water filtration for clean water." Bob thought the students had "vague prior knowledge about water filtering, they mostly relate it to something they heard in their own experiences such as a life straw."

In addition to student assets, both teachers also referenced the challenges they anticipated students would encounter and potential areas of growth. For example, when speaking about the specific practices within engineering design, Bob explained that students have an idea of how to design and build but they struggle to connect research to this process. Instead, students depended on the use of trial and error. According to Bob in the initial interview, the students have specific roles within their group in the project and this is used "as a way to highlight specific strengths of individual students or to see a different side of a particular student." Tom emphasized in the initial interview that students can use outside the classroom, or real life, experiences in engineering design even though they don't get a lot of experience with engineering design. This emphasis on using assets related to sensemaking and funds of knowledge was important to Tom who emphasized that "there is less biological engineering accessible to freshman students when compared to physical science." Neither teacher addressed how students could connect assets of their school or community within the engineering design project. Tom commented on a past activity where students would investigate a creek behind their high school to consider different ideas to decrease the amount of water pollution. According to Tom, this activity was not continued because water pollution mitigation efforts were already in use by the community so students could not develop any further engineering ideas for the creek.

> *[I]*t was very difficult as a lot of those things were no mow zones or a parking lot that uses filtering concrete and has a rain guard, and we would go look at all of that but it wasn't anything that they (students) could really test very well and so we decided to make it so that they can actually test what they were doing. (Bob, initial interview)

Both Bob and Tom explained that there was not enough time for students to use multiple design iterations thus limiting the use of student's expertise in this project. "*[I]*n a perfect world we would take the time to re-evaluate and redesign and remake until they're actually able to filter, but in this case, we are going to move on to our next unit now." (Bob, initial interview)

The introductory scenario on the student document provided students with information about global human access to clean water, a phenomenon in which students might have varied in their prior knowledge. The accompanying research guide provided students with specific websites for information about the region their water sample represented. Students were not required to have prior knowledge about that particular area of the world.

The document provided four roles for the students in each group, the project manager, the design tech, the engineer, and the scientist. There was a description of each role in the document giving the students the opportunity to determine which role would be best for each student in the group based upon prior knowledge and experiences with science, engineering, problem-solving, cooperative learning, and presentation skills.

The student document illustrated the requirement for students to use their assets of both technical and social expertise. The description of the problem and provided research websites related to the causes, effects, and regions of the water pollution attend to and support the social aspect of the design challenge and solution. Creating a design and prototype of a water filtration device along with the scientific water testing attended to and supported the technical aspect of the design challenge and solution. The selection of specific student roles was intended to highlight particular abilities or assets of individual students within a peer group. The specific student roles within the groups along with the specific research criteria from the research guide and the criteria from the presentation rubric, required both technical and social aspects to be used in the engineering design project, but individual students had the ability to select one or the other as their main responsibility within the project. Additionally, the accompanying research guide encouraged students to use multiple resources to leverage different forms of student expertise needed to complete the engineering design project.

The student document allowed students to express their ideas through the design and revision of a water filtration system. In the design section, students were to not only provide a written or computer-generated diagram of their design, but also written justifications of the use of each item in the design. This allowed the students to use their assets to select how the design was illustrated and justified. In the revision or improve step, students were given the opportunity to list what was successful in their design. Students needed to justify this using data collected and this allowed for differing ideas of what success was in designing. The same was true for the identification of what needed to be improved in the design. The last analysis question in the revision or improve section asked students to describe how they would change the design to include the identified improvements and to draw and label a new design. Student ideas could differ according to what they may have learned through the project and allowed for representation of individual expertise as an additional asset of the students within each peer group.

Included in the teacher-created presentation slides was a video about how toys are invented. This video focused on how one toy was invented based upon a mistake made in the design of something else. The video highlighted the process of designing a solution, the iterative process of designing and testing and how failure is part of success, and that success does not mean something worked perfectly. This video could support a classroom environment or safe space where success could be defined differently for each student. Each day of the project identified in the teacher-created presentation slides, labeled Monday through Friday included a short plan of action directed at all students and then specific tasks to be completed by each student role within the groups.

On day one of the project in both classes, students were to determine what role they would take within their cooperative group. In Tom's class taught by Sara, this process was not further supported by the teacher but left up to the students within each group to navigate the process of establishing individual roles. In Bob's class, Bob instructed the students to first read the descriptions of each role within the project and then to discuss these roles with other group members before making a decision. This process may have allowed students to think through the process of determining who would be best for each role based upon prior experiences and expertise or interests. The use of the student document each day of the project provided background information on the problem of clean drinking water to initial thoughts by students of what they already knew related to his problem and what information they still needed to find out. Having the specific steps of engineering design included in the document allowed students with varied experiences with engineering design to work through specific steps at specific times. The support of the use of this document varied greatly between the observations of the two classrooms and teachers. While Sara in Tom's class did reference the document throughout the project, there was no specific support of the use of the research guide, definition and identification of criteria and constraints, or the process of engineering design. Whereas in Bob's class, specific emphasis was placed on defining and identifying criteria and constraints, following specific steps of the engineering design process, and how to work through a redesign process. Students with less experience with engineering design were prompted during class each day to follow specific steps to approach a task in a specific way such as on day five when Bob prompted the entire class to first use data from the water tests to justify the revisions they made to their prototypes, and then to draw a new design including the needed materials, the cost of the materials, and an explanation of what each material is used for. This prompting of all students reinforced the allowance of all members of the group to support this revision process even though only the engineer was responsible for prototyping in the project. The feedback Bob gave to students on the final presentations in fifth period Biology did not specifically address the use of individual student assets.

Demonstration of Student Learning

The next theme that emerged from the analysis of the interviews was the demonstration and assessment of student learning. According to the planning done by the teachers, students were tasked with creating a presentation related to the water filtration engineering design project. As the creation of the interview questions was based upon specific components of the EQuIP rubric, the teachers emphasized how students would engage in a process that led to measurable learning. Both teachers discussed how using teacher-generated materials including a presentation rubric allowed them to identify observable evidence of designing solutions. In addition, it was stated that this rubric provided guidance to the students and supported Tom to provide teacher feedback to the students.

Throughout the initial and final interviews, both Bob and Tom identified how students should and did use knowledge and practices from the water filter design process to create a presentation. There was no attention to the application of this assessment to the biodiversity and human impact unit. The only standard addressed in the presentation is the engineering standard HS-ETS1-1, *analyze a global challenge*. In Bob's initial interview, this standard was described as what was assessed in the presentation and was therefore the focus of the content students should include in the presentation. Tom made a similar statement in the initial interview, but included that the students are assessed on their research of water quality and background on the specific pollutants and the steps of engineering design. Bob's final interview illustrated this assessment by elaborating that,

> now for the whole project to be successful right, they had to do quite a bit of research together, share out what they found within their research documents, and then design and build, that was a collaboration, even though they all had their individual components if they weren't sharing out what they researched their filter would not have overall probably been very successful, but then, when it came to actually grading them and how they scored on this project, they had to be able to present basically the research they did and the design, they did. (Bob, final interview)

This statement also highlighted the use of the individual student roles within the student groups by including individual responsibilities and the required collaboration of those in the process. Tom also identified student roles within the assessment in the initial interview by stating that the student's individual role was their only responsibility in the presentation which received a group grade. Both Bob and Tom explained that they use a standards-based grading system with levels of one to five. In order for an individual student to have earned a level five, they would have needed to make additional physical revisions to their filters outside of what was done in class. Both stated that their biology classes will move on to the next unit as there would not be enough time for the entire class to make revisions to their filters. Bob clarified that this is part of the engineering design process; "students should look at their results and decide if their design was successful or not and then students should decide what could make their design better which is considered the revision step of engineering design." In the final interview, Bob explained how feedback was given to students on a pre-constructed rubric.

> The students had the rubric that I was writing on as they were presenting and so I gave them back their rubrics, they had standard-based scores on them so four, three, two, one, and then I put comments on components that they were missing and explained why. (Bob, final interview)

When addressing how the feedback addressed ongoing learning, Bob replied that

> there's like a little checklist on the rubric and if they didn't hit one of those things on their checklist that they got marked down, they were just a little bit vague and not enough detail to fully understand the issue or problem that they were addressing, so it gets feedback in multiple ways, but that final feedback is on the rubric, and then they look at their feedback and then we talk about so you can redo and use your feedback to redo it or consider this feedback and think about how to use it, what skills we hit and how to use it in the future. (Bob, final interview)

The teacher-generated student document supported the process of engineering design and thus supported the demonstration of student learning. The student document provided a brief description of the problem of clean drinking water as means of providing initial support not only of the engineering design project itself, but also for the identification of the specific problem needing a design solution for each group. As the document outlined each step of the engineering design process, it also provided space for students to record information such as criteria and constraints, designs, and data from the water tests. As the final demonstration of learning was a presentation meant to include all of those items, this provided support for the student demonstration of this. Having an accompanying research guide to organize information and to prompt students to the importance of using research in the problem and design solutions further supported the final demonstration of learning through student presentations. The final item on the student handout was the presentation rubric for assessing student learning demonstrated in the final project presentations and is found in Appendix 2000.

While each day of the engineering design project included support for student learning related to engineering design, day five of the project was specifically for students to create the final presentations which was the only formal assessment of student learning in the project. Students in Tom's fourth hour Biology did not receive verbal support from Sara during this process. Students were creating presentations within their groups and decision-making as to what was acceptable evidence for the presentation on their own. In Bob's class, Bob moved from one student group to another asking students specific questions about the design of their prototypes, the effectiveness of the water filtration, and what improvements they were going to suggest for the water filter. For example, Bob asked one group what pollutants were identified in the initial water tests. Once the students responded, Bob asked "what parts of your design helped with what pollutant and how did your final water tests show this." Bob ended class on the fifth day by showing all students the presentation rubric on the classroom projector to remind students of what information should have been included in the presentations and how they would be assessed. As the feedback given by the teacher was on the presentation rubric and based solely on the students' final presentations of the engineering design project, all feedback was related to student demonstration of learning.

Summary

The first research question focused on how a high school biology teacher incorporates engineering in their biology classroom. The themes that emerged from the initial coding of teacher interviews, teacher-generated student materials and classroom observations of teaching encompassed this incorporation. While the direct link to the biology unit of study, specifically to science concepts, was weak or missing, the project did incorporate engineering design in a biology class. Use of the engineering standards in the teachers' unit plan and the teacher-generated student materials illustrated the attention to the engineering processes within biology class versus the support of the sense-making and use of biology concepts. While the intention of this project was to be a part of a unit on biodiversity and building upon prior learning through previous activities, it became apparent in the initial interviews that the project was more directed to the support of engineering design and the fulfillment of the NGSS engineering design standards.

While the teacher-generated materials were the same for both classes (Tom and Bob), the implementation of the project was different in each class as was the use of the teacher-generated materials. The classroom observations of each day of the project in both classes revealed these differences. In addition to the differing use of the materials, each physical classroom structure was different with Tom's classroom and laboratory being separated into two separate rooms. Bob's classroom was set up with traditional student desks in the front half of the room with a laboratory section of the room toward the back in which there was no physical separation. Being that Tom's class was taught by a substitute teacher (Sara) during the engineering design project, also led to differences in the instructions to students and the support of learning when compared to Bob's class. This points to key differences in the way an iterative engineering design project was incorporated into a biology classroom which leads to the second research question focusing on how students engaged in engineering design.

Research Question 2: How do high school students engage in an evidence-based iterative engineering design project in Biology?

Through initial coding of the classroom observations of students, the final student presentations, and the presentation feedback from Bob, several themes emerged surrounding how students engaged in the engineering design project. The themes that emerged through initial coding and analytic note-writing related included the iterative process of engineering design and the demonstration of student learning of engineering design and Biology.

This study included Tom's fourth hour Biology class which consisted of 25 students with twelve of those students providing appropriate permissions to participate in this study. The class was seated into groups of four students through the physical arrangement of student desks in the classroom. The student arrangement of the students into these groups was determined by Tom at some point prior to this study. This arrangement determined the groups for the engineering design project, and because of the number of students with permission to participate in the study, only one group of four students could be included in the study from Tom's class. The physical arrangement of the classroom space was such that the student desks, teacher desk overhead projector used for presentations, and materials for the water filter construction were in one room. Students had to travel through a short hallway into a second room used as laboratory space to do all water testing and testing of their water filter prototypes. Tom did not teach any of the engineering design project to the fourth hour students. Sara was a substitute teacher hired by the school to teach during the duration of the project included in this study.

Bob's fifth hour Biology class consisted of 27 students in which 25 of those students had the appropriate permissions to participate in this study. The class was seated into groups of four students through the physical arrangement of student desks in the front of the classroom. The student arrangement of the students into these groups was determined by Bob prior to this study. This arrangement determined the groups for the engineering design project, and because of the number of students with permission to participate in the study, six groups of four students were included in the study from Bob's class. The physical arrangement of the classroom space was such that the student desks, teacher desk overhead projector used for presentations, and materials for the water filter construction and laboratory area for construction and testing were in one room. The following figure lists the student groups included in this study from each class as well as an overview of what the students did each day of class. The names of each student group represent what water sample they were assigned to for the engineering design project. Table 4.3 outlines the daily tasks of the students in Tom's classroom which was taught by a substitute teacher and Table 4.4 outlines the daily tasks of the students in Bob's classroom. Both tables include whether the entire class was participating in the task or if individual groups were participating in a task.

Table 4.3

Tom's Student-Group Engineering Design Tasks Each Day of the Project

ED Tasks by Day	Student Group Uganda	
	Description of Tasks	
	Whole-class	Individual groups
Day 1	Watched a video about how a toy was invented Selected individual roles in their group Were assigned a water sample	Worked on steps 1-6 in the student document
Day 2	Sara prompted students to complete tasks 1-3 in the student document	Students worked on research, a design of a water filter, and the initial water tests of their water sample
Day 3		Gathered materials, constructed prototypes, tested prototypes by pouring water sample through
Day 4	Sara explained that scientists needed to complete water testing and all should be testing prototypes	Constructed and reconstructed water filter prototype, tested by pouring water through
Day 5	Sara prompted students to use the student document and accompanying research guide to complete their individual responsibilities for the presentation	Students worked on parts of the presentation and slides for the presentation
Day 6	Each group of students gave a presentation of the engineering design project	

Table 4.4

Bob's Student-Group Engineering Design Tasks Each Day of the Project

ED Tasks by Day	Student Groups Chicago, Bangladesh, Uganda, Des Moines, India, New York	
	Description of Tasks Whole-class	Individual groups
Day 1	Bob guided students through the student document and the accompanying research document Students selected their roles and the water sample they wanted to use for the project	Students worked on steps 1-2 of the student document
Day 2	Bob guided students through the student document	Students worked on steps 1-3 in the student document (identify the problem, research, and design) and the initial water tests of their water samples
Day 3	Bob reminded students to complete steps 1-4 in student document and then prompted to read steps 5 and 6	Gathered materials, constructed prototypes, tested prototypes by pouring water sample through them
Day 4	Bob directed students to step 7 in the student document and prompted students to complete step 7 and the final water tests	Reconstructing water filter prototypes, testing prototypes, and completing final water tests
Day 5	Bob prompted students to use the student document and accompanying research guide to complete their individual responsibilities for the presentation	Students worked on parts of the presentation and slides for the presentation
Day 6	Each group of students gave a presentation of the engineering design project	

(Table Continues)

Table 4.4 continued

Bob's Student-Group Engineering Design Tasks Each Day of the Project

ED Tasks by Day		Student Groups Chicago, Bangladesh, Uganda, Des Moines, India, New York
Day 6	Bob asked questions and provided feedback to student groups	

Iterative Process of Engineering Design

As previously examined through research question one, the intention of the two teachers was to use an iterative design process within the water filter engineering project used in class. Using the classroom observations of students, the engagement within the steps of engineering design was analyzed, examining also the iterations taken by the groups of students throughout the engineering design project. The following section provides evidence of students engaging in this process. The analysis of the classroom observations suggests that while the intention of the teachers was to emphasize the evidence-based nature of iterative engineering design, within the implementation of the project the evidence was varied in the nature of iteration and differed between the two classes.

On the first day of the engineering design project, the students included in the observation in Tom's fourth hour class taught by Sara began gathering filter materials and bringing them back to their desks. These students were engaging in impulse designing in which they were gathering materials and beginning building without having a well-informed design (Crismond, 2013). These students did not begin with step one in the student document which was to identify the problem needing a solution. These students also had not yet identified the pollutants in the specific water they were assigned. The students in the Uganda group were confused about the roles they had within the group. This led to only two of the four students working on the questions and websites on the research guide, while the other two members continued to work with the physical materials for the water filter. At the end of day one, this group identified the problem trying to be solved as “we are going to try to purify the human waste contaminated water using a filter system (bottle, coffee filters, sand, gravel, charcoal, etc.) and then sterilize the water once cleaned using heat (hot plate)”. It was clear from the use of specific prototype materials listed in the problem statement, that this group did not identify the problem prior to beginning the prototyping process. While the problem statement did include a specific pollutant of the water the group was using, this statement did not include all the pollutants in the sample water.

On the second day of the project in Tom’s class taught by Sara, the students in each group assigned to the scientist role moved into the laboratory room adjacent to the classroom to begin water testing. The other members of the groups remained in the classroom and were working on a one-dimensional design of a water filter and the cost of materials using the given websites on the research guide. Students were defining and identifying criteria and constraints on their own. The definition of the term criteria was included in the student document and the students in the Uganda group interpreted the criteria of the design as “the system must filter the waste apart from the water and the system must sterilize the water of any harmful bacteria using heat.” This criterion closely matched that of the group’s identified problem trying to be solved. The term constraints was also defined on the student document and the Uganda group interpreted this to mean “lack of material could mean the system as a whole may not work and the system may be too heavy to hold on a stand.” This group was able to identify the limited amount of materials for use in the classroom as a constraint but did not identify the time given to design and build a water filter or the maximum allowable cost of fifteen dollars for the filter as constraints. For the Uganda water group in Tom's classroom, the student assigned as the project manager moved into the laboratory area to assist the scientist with the water testing. The two remaining students, the designer and the engineer stayed in the classroom. The designer used the student document to draw a design of the water filter they planned to build. Students were prompted by Sara to only go through the design step in the student document and then to stop. The scientist and project manager for the Uganda group returned to the classroom and the scientist explained to the other two members that "we have plastics and coliform bacteria from human and animal waste" in their water sample. From the Uganda group's shared student document, it could be seen that the group identified only plastics and materials in the water before filtration (see Figure 4.4).

Figure 4.4

Uganda Group's Water Testing Data Table (Tom's Class)

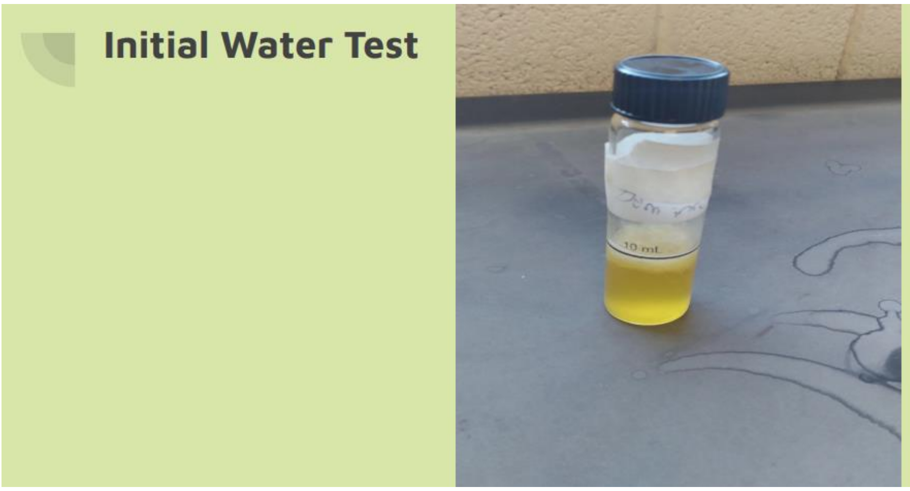
Tests	Before Filtration System	After Filtration System	Ideal Water Conditions	Is Your Final Filtered Water Safe to Drink Based on Results
Smell	BAD	A lot better, but still a small smell	Close, but not 100% clean	Probably not
Description of what water looks like (before and after pics are helpful here to see water clarity changes)	Had plastic and a few materials in it	No plastic, but still had a few charcoal materials in it.	Not 100% but no plastic was visible	With this in consideration yes, but if allo factors are in consideration, no.
Identify the Pollutants here: ___________ ___________ How much of the pollutant was found? (level)	Plastic and materials	A few materials, and no plastic is visible.	No pollutants except some materials	No, because there are some small materials in it.

Note. Uganda water group in Tom's class

However, as could be seen in the Uganda group's presentation, they illustrated the presence of coliform bacteria from waste or sewage in slide nine titled initial water test with a picture of the water testing vial used to run the coliform bacteria test on the water sample as seen in Figure 4.5.

Figure 4.5

Uganda Group's Final Presentation Slide Nine



Note. Uganda water group in Tom's class

The Uganda group identified bacteria in both the statement of the problem and the design criteria but did not include this as an identification of a pollutant in their data table nor did they provide data of the initial and final testing of the water for coliform bacteria. This group did however include the identification and initial testing of the water for coliform bacteria in their final project presentation.

On day three of the project in both Bob and Tom's class, all groups were gathering materials and working to build a prototype of the water filter they designed the previous day. The Uganda group in Tom's class took less than 20 minutes to construct a prototype of their designed filter. While constructing the filter, the group's project manager commented "this is not going to work, the water will not go through the sand." The group considered this and chose to continue to make the prototype based upon their original design. The scientist in this group asked Sara, the substitute teacher if they will be testing the prototype. Sara responded that "once your filter is done, you should test it." The Uganda group tested the water filter in the laboratory room with the scientist pouring the Uganda water sample into the top of the filter and collecting what water came out of the bottom of the filter. The project manager assisted by holding the filter as it is not self-supported. Both group members observed the water and noted that there were no plastics in the water but that the water was coming out of the filter much darker than it went in. The students considered whether they should perform any other tests on the water, but then continued to pour more water through the filter. The scientist and project manager decided to take the filter back to the rest of the group to consider a redesign. The engineer stated that adding a coffee filter to the existing prototype would remove the dark color from the water. The designer in the group chose instead to remove some of the charcoal from the prototype and to add more sand and gravel to replace the charcoal. None of the Uganda group members referenced any of the given research during this redesign process. The scientist and project manager then returned to the laboratory room with the redesigned filter and poured more Uganda water through the filter. The scientist noted that the water coming out of the bottom of the filter was still brown and black. The group did not set up a second coliform bacteria test on the filtered water. The scientist stored the prototype in the laboratory room when class ended.

On day four in Tom's fourth hour class, the designer and engineer in the Uganda group decided to create a new water filter using a new bottle found in the classroom materials. The project manager and scientist used the provided research guide which was to be completed on day one of the project for ideas of how to make a new water filter. The entire group discussed the layer of materials they wanted in the filter, but the group did not research or discuss the purpose of the materials or order of materials for water filtration. Together, all four members of the group built a new water filter and then took the newly created filter into the laboratory room and tested it using more of the Uganda water sample. The scientist noted that the water coming out of the bottom of the filter was still black. The entire group considered a redesign of the new filter, but no one referred to any type of research to do this. The group added more of the existing materials in the same layers as before and retested the filter. The group noted with this new test that no water will move through the filter, and they redesigned again. With this newest design, the group was able to collect a small amount of water at the bottom of the filter that was determined to be visibly clear by the engineer of the group. The scientist of the group determined that there is not enough water to run the needed water tests. The designer of the group then determined that their original design of their water filter included boiling the water after it was filtered, but that the group did not purchase a beaker to do this. The group chose not to boil the water or to do any further testing.

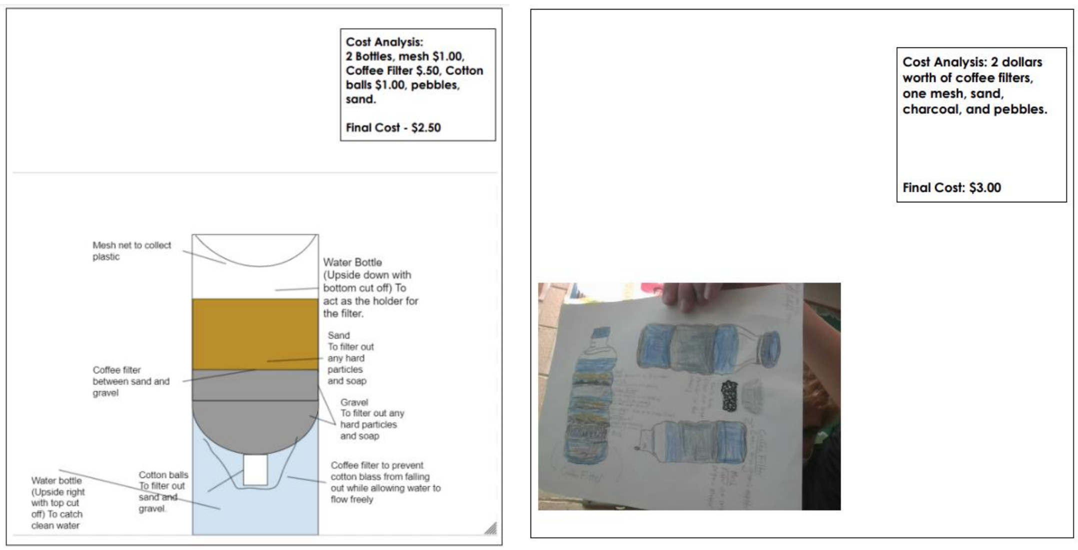
While the Uganda group did engage in the iterative process of engineering design, there were possible alternatives to this iteration that could have led to a more successful engineering design process. One such alternative could have been to revisit the research step based upon the results of the testing process and then on to the design step prior to additional prototyping and testing. While the group was able to use the teacher-generated student document to facilitate the process, there were errors in identification of constraints, the water testing data and the design process itself. The lack of intervention of instruction by the substitute teacher may have led to a less successful use of the iterative engineering design process. "Students need instruction and practice to help them see problems in design, identify and determine the causes, and fix them" (Crismond, 2013, p. 52).

On day one in Bob's fifth hour class, once the students assigned roles, one member of each group was tasked with selecting a beaker of water for their group so they could begin their research. All students in Bob's class were prompted to read through the teacher-generated student document prior to continuing any further work on the project. Once students read the document, Bob asked for a student to volunteer the answer to the problem they were to be solving and one student responded that it was to make clean drinking water. All students in the groups were then completing the questions on the research guide at the same time. Before the end of class, Bob defined the term constraints and explained that the materials provided in the classroom were an example of this. The students did not have to identify the constraints of the project themselves. Students were given support of the completion of specific steps within engineering design but were not given the freedom to select an alternate route for the process.

On the second day of the engineering design project in Bob's fifth hour class, the students assigned as scientists moved to the laboratory area within the classroom and worked on the initial water tests. The other students in each group worked together to design a water filter. Some groups made diagrams on paper of filter ideas while others used the online student document to create a diagram of a filter. See Figure 4.6 for two examples of different designs.

Figure 4.6

Examples of Designs Made in Bob’s Class



Students worked to add materials from the list into a cost analysis for the filter design. At the end of the class period, Bob returned the entire class to their individual seats and explained that all groups should have completed steps one through four in the student document and that the first column on the water testing in step five called initial testing should be complete. Bob then defined both the term criteria and the term constraints for the entire class. Bob asked a student to volunteer an answer to the question of what the criteria of the design was, and one student responded with “to create clean water by making a water filter.” Students were then instructed to make this specific to the pollutants they identified through research and water testing. This idea was interpreted differently by the different groups of students. For example, the Chicago water group stated the design criteria as “filter out pollutants to create clean drinking water and bring pH to safe drinking level,” in which they did not indicate the specific pollutants, whereas the Bangladesh water group identified their design criteria as “must filter out organic matter and must filter out soap/detergent in water to make it safe for drinking.” This group had previously identified organic matter and soap or detergent as the specific pollutants in their water sample. The New York group also identified the specific pollutants found in their water sample but also added the maximum cost of materials being fifteen dollars to the design criteria on their student document.

The students were then asked as a class what the constraints of the design were, and a student responded with time, materials, and money. Each student group in Bob's class included these three items and nothing further in their lists of constraints on their student documents with the exception of the India group which did not include the materials. An interesting note was that some groups simply included just the term "materials" or a statement similar to "what materials they were able to use" whereas two student groups listed a constraint of "access to materials" more consistent to the application of this idea to the area of the world the water sample represented.

On the third day of the project in both Bob and Tom's classes, all groups were gathering materials and working to build a prototype of the water filter they designed the previous day. All students in Bob's class then moved to the lab tables in the back of the room with their groups. Students collected materials and began to construct the prototypes of their designed water filters. Some students were working to redesign their original design as they built their prototype. For example, the Bangladesh water group noted that the bottle used to make the outside structure of the water filter was taller than what they wanted it to be. They discussed how much of each material they believed should be included inside the bottle before cutting the bottle shorter. They were engaging in an iterative process by revisiting the design step before completing the initial prototyping and testing steps. The process was neither encouraged nor discouraged by the teacher. The Chicago water group discussed how much of each material needed to be included in their prototype. They referred back to their design and cost analysis and pointed out that the exact amount of coffee filters, sand, gravel, and cotton balls were not previously discussed or listed. Two members of this group referred back to the student research guide to identify what each material would help to filter before deciding the amount of each material for the filter. This was another example of the iterative process in which students used the prototyping step of engineering design to determine a design weakness and then referred back to the research and design step before continuing the prototyping step. The groups took approximately the same amount of time as Tom's students did to build a first prototype of a water filter. Groups then began collecting water from their filters. Bob prompted the entire class to "re-evaluate the materials included in your designs as you make changes to the physical model." This statement reinforced the process both the Bangladesh and Chicago water groups engaged in prior to this reinforcement by the teacher. Those groups who completed the required initial coliform bacteria test used a sample of their newly filtered water to set up the test at the end of day three. At the end of class, Bob had students store the prototype water filters in the lab area and return to their normal classroom seating. Bob reminded students that their prototypes needed to be completed that day and that the coliform bacteria test needed to be set up for those groups with human waste or sewage in their water.

On day four of the engineering design project, all student groups in Bob's class chose to make further revisions to their existing water filters versus making a new filter. All groups chose to engage in the revision step of the engineering design process. The Bangladesh group tested their initial prototype and noted that the water coming from the bottom of the filter was visibly clearer; however, when the scientist tested the pH of the water, it was the same as the pH of the initial water. All four members of the group discussed a revision to their water filter which included the elimination of some of the materials in the filter and the addition of other materials. None of the group members accessed or discussed the given research guide to make a decision about what materials to remove or add. While the group was using testing results to identify that a revision should occur, those revisions were not based upon what was present or absent in the tested water. After making revisions to their water filter, the Bangladesh group tested it again with similar results. The scientist noted that while the water collected from the filter was clear and the pH had improved, the pH was still not good enough according to the acceptable levels of pH listed in the student document. The group discussed further revisions without using research and noted those suggestions in their student document. The group chose not to continue to make those revisions to their water filter. The Bangladesh water group had engaged in evidence-based changes to their original design on the previous day using the prototyping process to inform this decision but were not successful in engaging in evidence-based revisions of the prototype on the fourth and final day of prototyping and revising.

Demonstration of Student Learning-Engineering Design

Included in the iterative process of design within this engineering design project was the creation of a final presentation of the project by each student group. This final presentation was used as a measurement of the demonstration of what students had learned through the process of the project. Students were provided opportunities to demonstrate learning of the engineering design process. Also included with the final presentation of learning was written feedback given to students in Bob's class.

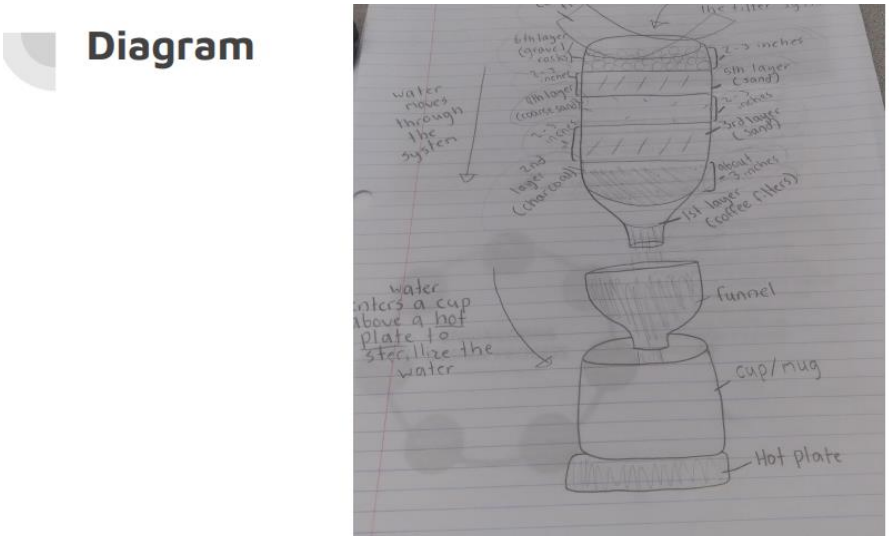
On day five, Sara prompted the students in Tom's class to complete their presentation and slides for the presentation. Students in Tom's class spent the rest of class time creating slides for the presentation and writing notes of what to present without the assistance of

Sara. The students in the Uganda group used the rubric to divide responsibilities within a slide show the project manager created and then shared with the group. The group members focused on completion of the slides and presentation notes and there was no discussion of the engineering process or the success of their water filter.

Day six, which was the last day of the water filter engineering design project in both classrooms, consisted of student group presentations. In Tom's class, the Uganda water group's presentation began with the project manager stating the problem as "trying to purify human waste-contaminated water using a filter system and then sterilize the water once cleaned using heat." This student also identified the criteria of the project as "to make the water clean," and the constraints as the materials and resources available to use and the amount of money they could spend. This statement differed from that of what this group had previously identified as constraints in the student document. The Uganda group did not elaborate on the problem by including references to how clean water is a global problem or the possible health or environmental effects of the water pollution in Uganda. The designer of the group then displayed a slide found in Figure 4.7 with a diagram of their water filter design and explained what materials the group used in the design and in what order they added those materials to a bottle to make the filter.

Figure 4.7

Uganda Group's Final Presentation Slide Three

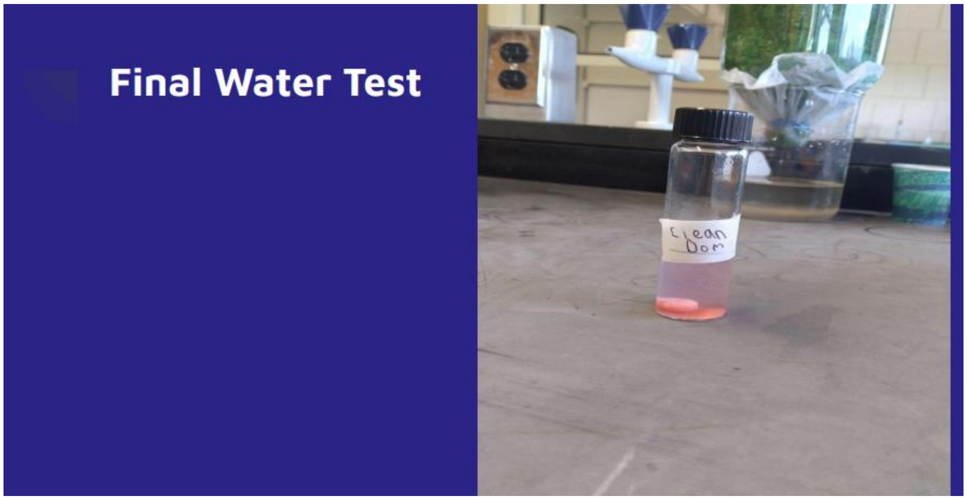


Note. Uganda water group in Tom's class

The designer also listed what each material was to filter in the water such as a coffee filter to stop the plastics from moving through the filter. It was assumed the justification of the materials was evidence-based using the provided teacher-generated research guide. The engineer in the group then stated that there was a final step to end the filtration system which was boiling the water. It was noted in the classroom observations that the Uganda group did not boil the water collected from the water filter, but this was not stated in the presentation. The scientist provided the initial water tests results as having a bad smell, containing human and animal waste, and having plastics and a few other materials in it. It was stated that the results of the initial coliform bacteria test were positive for coliform bacteria. The scientist stated that the final results after filtering the water was that the water still had a small smell, no plastics, but had a dark color to it due to the charcoal in the filter. As noted previously, this group did not perform a final coliform bacteria test on their filtered water, however a picture of a negative test was used in the presentation slides and was labeled as the final water test (see Figure 4.8).

Figure 4.8

Uganda Group's Final Presentation Slide 10



Note. Uganda water group in Tom's class

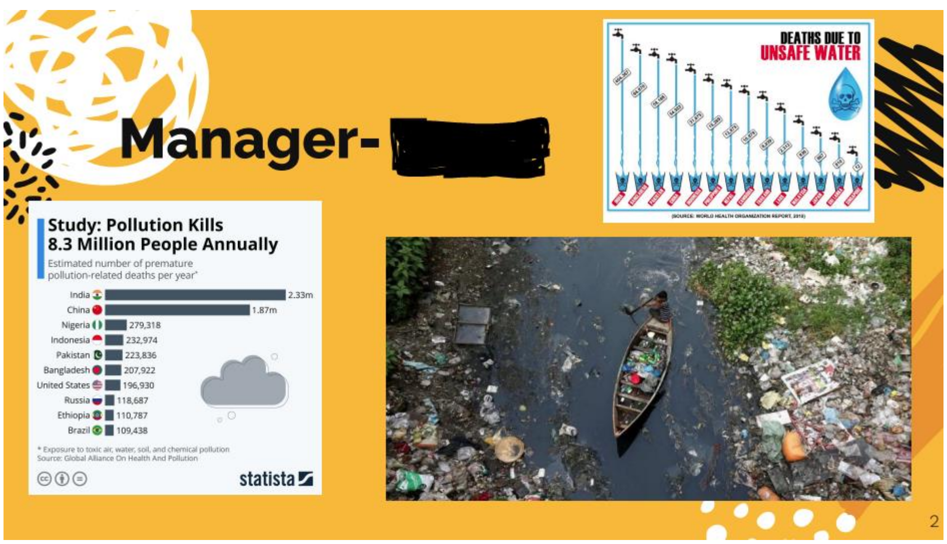
The engineer of the Uganda group then explained that the group would change the amount of coffee filters used in the water filter so more water would move through the filter and that all of the coffee filters would be at the bottom of the filter to get rid of the charcoal color of the filtered water. It was not stated as to whether these revisions were evidence-based with relation to researching what the materials would filter from the water. The Uganda group did use evidence from the water testing to propose changes such as adding coffee filters to remove the charcoal color from the water. Students did not have any questions or feedback from Sara to respond to during or after their presentations. It seems from the missing items in the presentation such as not mentioning they did not boil the water and the addition of a final coliform bacteria test which the group did not complete during the project, this group may have presented what they believed to be the correct answers versus demonstrating what they learned through the engineering design process. According to Sung and Kelley (2019), designers sometimes use a solution-focused approach with the belief that a task or problem can be solved with a single, correct answer.

On day five in Bob's class, the students worked to create presentation slides and notes of what information to present the following day. Bob moved from one group to another asking the students questions about their designs and research.

The last day of the water filter engineering project or day six, in both classrooms consisted of student group presentations. The Bangladesh water group in Tom's class began their presentation with the project manager explaining where their water came from and the specific problems with the water as being the water was stinky, brown and included organic pollutants and soap. The project manager also stated that the "National Library of Medicine website identified organic pollutants and the Citizen Matters website identified soap as a pollutant also." This group included two graphics of statistics related to water and pollution found from online research done (See Figure 4.9).

Figure 4.9

Bangladesh Group's Final Presentation Slide Two



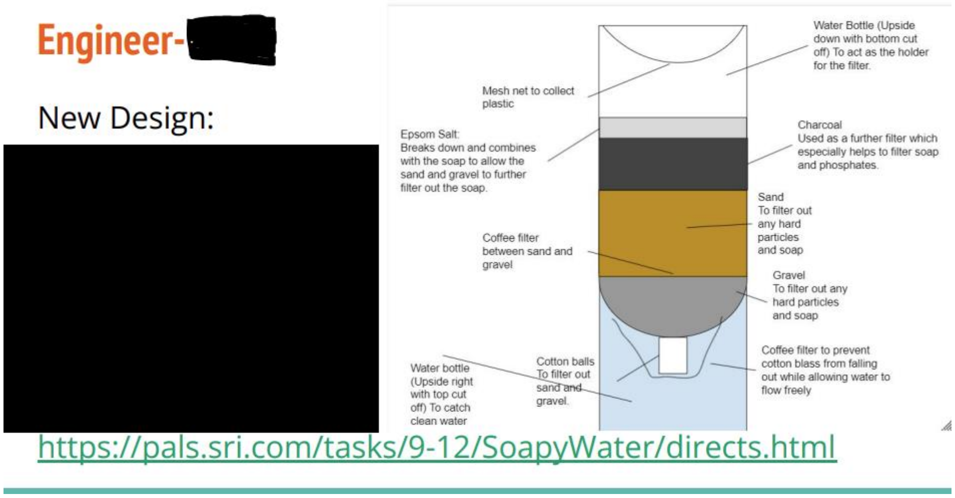
Note. Bangladesh water group in Bob's class

The project manager identified the criteria of the project as removing organic material and soap from the water to make it safe to use and the constraints being the materials they could use and how much the filter could cost. The designer explained the specific materials found in layers within the water filter they designed. This student elaborated by identifying what each material in the filter would filter out in the specific Bangladesh water sample they were using. For example, in both the designer slide and in the presentation, it was explained that the material called mesh would filter out large organic matter. The scientist of the group listed the results from the initial water tests as the water was stinky and brown and contained organic pollutants and soap. This student stated that an initial pH test was done on the water and the pH was nine. The scientist explained that the water tested after being filtered had no smell, color or floating material, but the soap was not well filtered as the final pH test was still nine. The engineer of the Bangladesh group stated that their water filter had filtered out the organic matter because the water did not smell, and the color of the water changed from brown to clear. This student pointed out that the soap was not well filtered because the final pH of the water was still nine. The engineer explained potential weaknesses of their filter as there was not enough sand, charcoal, and pebbles layered and packed together in the filter. It was implied that these weaknesses were identified from the testing process but was not explicitly stated. The engineer also pointed out the use of Epsom salt in their filter as a possible redesign option as that would create soap scum which they could then filter out through adding more mesh to the filter. This student also stated that “there has also been minimal research done to show that freshly squeezed or bottled lemon juice can lower pH points by 1.5.” This student did not elaborate on how or when lemon juice would be included in a redesign of their water filter. The engineer was attempting to address revisions of the design of a water filter using the specific water pH testing results as a component of an evidence-based iterative engineering design process.

The Chicago water group had a similar presentation with the statement of the problem and criteria of the project by the project manager as being specific, "create a water filter to filter out Chicago water pollutants and bring pH to a safe level to create drinkable water." The constraints were listed as time, material, and money for the project. While global statistics were used to establish the problem, this group did not explain how plastics or detergent in the drinking water was a problem to humans or the environment. The designer of the Chicago water group included the cost of the materials used and the final cost of the water filter in both the slide used for the presentation and in his explanation of the design. This student also included an explanation of what most materials would filter out, or their purpose in the water filter. Unique to this group, was an explanation in the design of specific materials that had a purpose related to the other materials used in the filter. For example, it is stated in the design that the sand and gravel would filter out hard particles and soap, and that cotton balls would filter out the sand and gravel that got into the water from the filter. The scientist also presented initial and final water test results to demonstrate some success of the water filtering process. The engineer presented a new design that included the addition of charcoal which was one of the classroom materials and the addition of Epsom salt which was not one of the materials available to them as seen in Figure 4.10.

Figure 4.10

Chicago Group's Final Presentation Slide Five



Note. Chicago water group in Bob's class

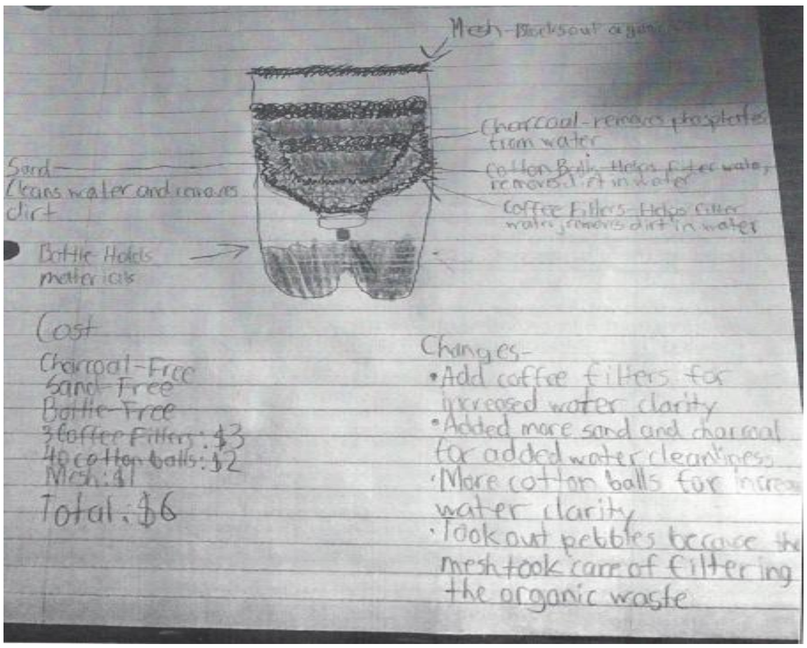
It was stated in both the slide for the presentation and in the explanation that epsom salt breaks down the soap to allow the sand and gravel to further filter out the soap. The engineer also included the website where this new design was found as justification for the redesign. It was not specifically stated that the final pH water test result was the reason for this redesign. This illustrated that while the group engaged in an iterative process, they either did not engage in an evidence-based revision process or did not present the evidence-based process they used to create this revised design.

The New York water group was not able to fully identify water quality as a global issue. The project manager identified the pollutants in the water but did not explain what problems could be caused by having these pollutants in drinking water. This group was not able to clearly illustrate the water testing or prototype testing. They did not include any data from the initial or final water testing they did earlier in the project. Interestingly, the initial and final water testing data was included in the student document this group was using during the engineering design process. This group did however also suggest a redesign of their water filter prototype using both classroom materials and a material outside of those included in the project. This group explained that they redesigned in the classroom by removing the gravel they had originally used in their filter and added sand and cotton balls. This group also chose to move the layer of clay to a different position in their filter to remove a discoloration of the filtered water. The engineer proposed the addition of sodium carbonate to the filter as a means of increasing the pH of the water. While the New York group was unable to communicate through the presentation that they engaged in evidence-based iterations, the classroom observations and student work during the project did illustrate this process.

The India water group struggled to provide information about the global issue of water quality. This group identified the specific pollutants found in their water sample, but only stated that these pollutants could cause disease. There was no elaboration on what diseases could occur in humans or other living things and there was no reference to the websites included in the student research guide provided at the beginning of the project. The India group identified appropriate criteria of the design by including the specific water pollutants to be filtered as phosphorus and organic pollution in India's water, but only stated the time given to make a prototype as the constraints of the design. This group did not include the materials or cost in the constraints. The India group struggled to explain how to redesign their water filter to be more successful. While the group was clear on the design of their filter, presenting the materials used and a justification of those materials through the testing of their prototype, the engineer's suggestion of including aluminum salts did not address the findings of their final water tests where they stated that the water was still cloudy due to organic material. The engineer explained that the addition of aluminum salts could further lower the phosphorus levels in the water. Interestingly, this group addressed the remaining organic materials in the water after filtering by proposing changes to their existing prototype using materials from the classroom in the student document which is illustrated in Figure 4.11.

Figure 4.11

India Group's Student Document Design Improvements

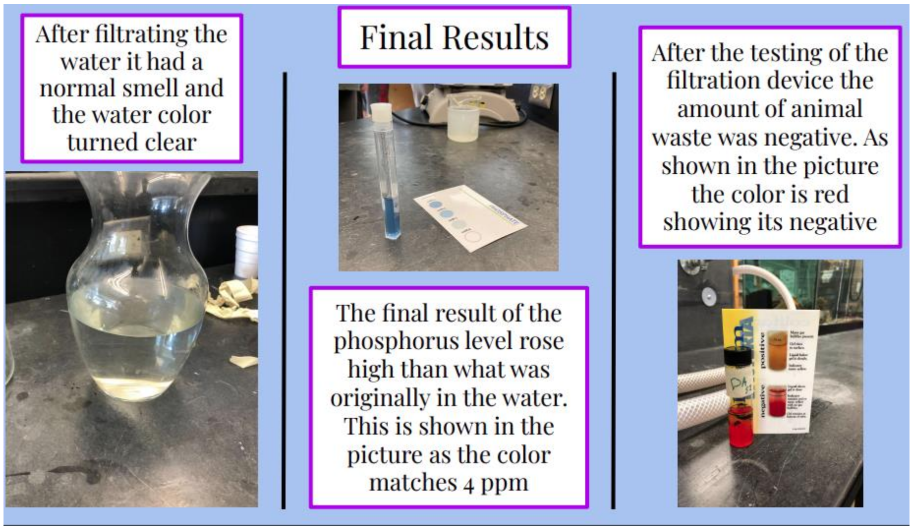


Note. India water group in Bob's class

The Des Moines water group clearly identified the global and local issue of water quality through the use of research. The project manager also identified the specific pollutants in the water sample and explained why this was a problem to humans and included appropriate criteria and constraints. This group also clearly presented their design, prototype, and water testing. The final water tests were clearly identified in the presentation, but a unique outcome occurred where the students found an increase in the level of phosphorus after filtering the water as seen in Figure 4.12. The designer in the group did not elaborate on the strengths or weaknesses of the water filter given this outcome.

Figure 4.12

Des Moines Group's Final Presentation Slide Six



Note. Des Moines water group in Bob's class

The engineer of this group proposed an idea of a redesign of the water filter using a mining by-product, called mine drainage ochre, to remove more phosphorus as the scientist of the group indicated that the phosphorus level increased from the initial to the final water test. The identification of a specific revision based upon the results of the final water testing illustrated the engagement in an evidence-based iteration of engineering design even though this group did not indicate investigating why the phosphorus level increased as a result of filtering the water.

The Uganda water group in Bob's class clearly identified the global and local issue of water quality through the use of research. The project manager also identified the specific pollutants in the water sample and explained why this was a problem for people in Uganda and included appropriate criteria and constraints. This group's explanation of the water filter prototype included the components of the filter, but they did not discuss why those materials were used or why they were placed in layers within the filter. The Uganda water group also had a suggestion of a redesign using materials outside of those included in the project and identified as constraints. This group suggested a water filtration system not based upon the filtering system they prototyped in the engineering design project. The engineer of this group proposed using a reverse osmosis filtering system instead of their water filter design. The engineer stated that this system worked by using a pre-filter to remove chlorine and sediment and, when asked by Bob during the presentation, estimated the cost of this system as fifty to one hundred dollars. The Uganda water group either did not conduct research prior to the design of a water filter or complete initial and final water testing during the project or was not able to present the research and testing used. It is not known whether the inability to demonstrate the use of evidence-based iterative engineering design was by error in the presentation or due to the lack of engagement in the project prior to the presentation. It was evident from the presentation of the proposed revision that the revision selection was not evidence-based using the initial and final water testing results or research done using the provided websites specific to the water sample selected by the group.

The students in Tom's class did not receive any feedback from the teacher. Bob provided written feedback on the presentation rubric (see Appendix 600) to each student group after the completion of all of the presentations. The feedback provided to each group is listed here in Table 4.5.

Table 4.5

Written Teacher Feedback to Student Groups (Bob's Class)

Student Group	Section of Rubric	Written Feedback
Chicago	Define the Problem	good statistics to define problem and how is plastic/detergent problematic for drinking water
	Criteria & Constraints	used plastic and detergent in criteria
Bangladesh	Define the Problem	includes human diseases caused by water pollution
	Criteria & Constraints	identifies organic materials and detergent, but constraints needed to be more specific than just time and money
	Developing a Solution	no research referenced
	Revising	need to be more specific on how lemon juice affects drinking water
Uganda	Define the Problem	good research
	Criteria & Constraints	identified human waste and plastics
	Developing a Solution	need to label components of filter
	Revising	no new design, did not reference test results for basis of new design, no cost analysis, reverse osmosis - had research but could not explain how or cost
Des Moines	Criteria & Constraints	identified animal waste and plastics
	Testing	clearly state the strengths/weaknesses of filter based upon your test results
India	Define the Problem	discuss drinking water as a worldwide problem as well, reference CDC website
	Criteria & Constraints	identified plastics and organic material, only one constraint mentioned and what about affordability

(Table continues)

Table 4.5 continued

Written Teacher Feedback to Student Groups (Bob's Class)

Student Group	Section of Rubric	Written Feedback
	Prototyping	"blocks stuff" - what stuff
	Revising	maybe consider if water not completely clear, you are not filtering all organic material and should address this issue as well
New York	Define the Problem	discusses drinking water problem worldwide but does not explain why specific pollutants are problematic in drinking water
	Criteria & Constraints	identifies acid and plastic in criteria
	Testing	have actual data on slide, smell-visual of water not included no images of experiment to show effectiveness

The feedback identified areas of strength and weakness related to the specific sections of the engineering design process which were included in the presentations and the rubric used to assess the presentations. Feedback targeted areas of defining the problem and criteria and constraints more than other areas of the presentations.

From the classroom observations of the students during the engineering design project, it was evident that all students included in this study engaged in some form of engineering design. While the students in Tom's class did not receive the same type of instructional support from the teacher, members of the Uganda water group engaged in every engineering design step included in the teacher-generated student document. This group's presentation reinforced the observation of the use of engineering design by demonstrating that they had researched how to design a water filter, they designed a water filter on paper and were able to construct a prototype of their design. The inconsistencies between the presentation and the classroom observations illustrated areas of engineering design where the students struggled to effectively engage in learning and practices related to engineering design. While the students were able to demonstrate the iterative nature of the engineering design process by communicating revisions and retesting, the students missed opportunities to engage in evidence-based decision-making by not completing the appropriate water tests, prototyping processes, and research of the pollutants and water filter construction. The students in Bob's class received more direct instruction related to the process of the engineering design project but had similar results. While several student groups were able to demonstrate their engagement in engineering design through their presentations, other groups had less successful presentations. This was true for the New York water group in which the students completed initial and final water testing and tested their prototype during the project but did not communicate information about the water or prototype testing in the presentation. Multiple groups including the Bangladesh water group were able to identify possible revisions to their prototype but were not able to fully explain why those revisions should be made or what evidence was used to come to this decision. It was stated earlier that all student groups in Bob's class were able to physically implement revisions to their original prototypes. This illustrated the engagement in the iterative nature of the engineering design process; however, most groups did not elaborate on this process in their presentations but instead explained other possible revisions to further improve upon their last prototype tested.

Demonstration of Student Learning-Biology

The water filter engineering design project was part of a curricular unit of biology called biodiversity and human impacts on biodiversity. The specific NGSS performance expectation identified for the project was HS-LS2-7, *design, evaluate, and refine a solution for reducing the* *impacts of human activities on the environment and biodiversity*. Prior to engaging in this project, students worked through a case study of water pollution in a river, identifying sources of the pollutants, human and environmental impacts of those pollutants, and possible solutions to reduce the amount of pollution in the river.

Biology was mostly missing from the student engagement in engineering design. The most apparent connection to the life science standard was the identification of the problem and specific research about the pollutants in the water and the health effects on humans which was in the first step of the planned evidence-based iterative engineering design project. From the classroom observations and the student presentations, the focus was on identifying the pollutants in the water but not on how human activity contributed to the problem or how to reduce the impact the human activity was having related to water pollution. It was clear from the student group presentations and teacher feedback that not all students connected the need for clean drinking water to human health, the biodiversity on Earth, or the impact human activity has on biodiversity. Students did not clearly identify the source of the water pollution as an activity but instead as a thing such as organic material or detergent. For example, the Chicago group in Bob's class identified the pollutants and thus the specific criteria for filtering as detergent and plastics. This group did not include how those pollutants entered the drinking water. While this group did define the specific problem to be solved was to bring the pH of the water to a safe level, the group did not elaborate on why this has an impact on living things such as humans. From the information provided in Bangladesh water group's presentation in Bob's class, attention to drinking water safety for humans was illustrated. This group included statistics of the number of human deaths world-wide related to unclean drinking water. This student group, like that of the rest of the class, did not include any references to the environment or biodiversity. The engineering design project process did not clearly support the connection between the activities that created water pollution to the activities' impact on biodiversity or how creating water filtration devices was a human activity that can impact biodiversity as well. Evidence of biology-specific phenomena is missing from the classroom observations of students and the student group presentations.

When students engaged in designing a solution through the engineering design project, little connection was made between the identification of materials and processes used to filter water and the scientific aspects of the pollutants. For example, some student groups determined that boiling water could remove organic materials but did not make a connection to how boiling water actually caused this or how it could impact biodiversity. There were only implied effects of filtering water on humans such as reduced illness and death, but this was not explicitly part of the project. The Uganda group in Tom’s class stated in their presentation that the specific problem was to purify and then sterilize water to make it clean. One could conclude that the sterilization process was an important part of cleaning water, but this group did not get to that part of the prototype process, and this was not noted in the presentation. There was no connection made to what sterilization was, how it could be achieved, and what impact this could have on humans and biodiversity. This limited the students’ ability to demonstrate their knowledge of designing effective solutions to scientific problems as stated in the associated NGSS performance expectation.

Summary

This chapter provided evidence of how the two biology teachers in this study planned the incorporation of engineering design into biology class. The teachers selected the curricular unit on biodiversity and human impacts on biodiversity for the incorporation of an engineering design project. Activities prior to the engineering design project attended to a specific NGSS performance expectation not included in the project. The teachers selected two NGSS performance expectations for the engineering design project in which student groups created water filters. There was a focus on the incorporation of the iterative process of engineering design and the consideration of the assets of students who would be engaging in this process. The teachers in the study were using a standards-based curriculum and grading system, and therefore also attended to how students would demonstrate learning of Biology related to the unit and of engineering design driven by selected NGSS performance expectations in both the planning and implementation of the project. Students engaged in a six-day engineering design project in which they moved through a series of engineering design steps selected by the teachers. Students engaged in the iterative nature of engineering design through redesigning and retesting prototypes before giving final presentations. This followed the NGSS engineering performance expectation selected by the teachers during planning which was 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*. Students gave final presentations of the engineering design project as a means of demonstrating learning related to biology and engineering design. One teacher provided written feedback to the students related to the final presentations which addressed mostly engineering design. Both the incorporation of engineering design by the teachers and the engagement in engineering design by the students lacked clear connections to biology content and the included NGSS life science performance expectation used to plan the project of HS-LS2-7 *design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity*.

CHAPTER V: CONCLUSION

Chapter I presented the ongoing challenge of integrating engineering design into science as guided by the *Framework* and the Next Generation Science Standards (NGSS). The goals for science learning and teaching included in the *Framework* have changed the focus of science education from memorizing content and practicing inquiry in isolation to building and applying science knowledge (Krajcik et al., 2014). Included in the NGSS is the integration of engineering practices into science instruction. According to Mentzer et al. (2015), the standards establish engineering as a fundamental part of science learning as students are expected to transfer science knowledge through the science and engineering practices. The NGSS provide recommendations such as attending to and prioritizing a range of criteria and constraints, breaking a problem into smaller parts, and assessing the impacts of solutions, but do not define how teachers should integrate science and engineering (Hite, et al., 2020). This creates an even more complex situation for science teachers to define what engineering is in relation to three-dimensional learning when planning lessons and curriculum. The *Framework* provides further explanation of how engineering practices should be integrated in a multidisciplinary way to support scientific problem-solving within a context of the real world without defining how specifically a teacher should incorporate engineering into science. This has been specifically challenging with the life sciences and the research regarding engineering design in the life sciences is limited. Nadelson, et al. (2016), argued that this is due to teacher preparation and prior experiences not including innovations in science education such as engineering design. In classrooms where engineering design is included, "teachers may be attempting to engage their students in engineering, but their perceptions and ideas of what constitutes engineering may be limited" (Nadelson, et al., 2016, p. 6). If teachers are not confident or practiced in the use of engineering design, they may rely on more traditional teaching approaches to incorporating engineering design into science. This could constrain not only the ability for students to learn engineering design, but also the science concepts targeted in the incorporation of engineering design. The purpose of this qualitative case study was to explore the incorporation of engineering design in high school biology classrooms. Specifically, the teachers in the study identified the use of multidimensional standards in the classroom. The specific engineering design challenge created and used by the teachers in this study targeted specific NGSS performance expectations for life science and engineering. This chapter provides a summary of the findings for this study which was implemented to explore the following research questions:

1) How does a high school Biology teacher incorporate engineering design into their biology classroom?
2) How do high school students engage in an evidence-based iterative engineering design project in biology?

Included will be a discussion of the findings, their connection to existing literature, and the research necessary to inform future work in integrating biology and engineering. Also included is a discussion of future research and implications for educators and schools as they look at how to improve the science and engineering experiences of high school Biology students as well as the limitations of this study.

The Incorporation of Engineering Design into Biology

This qualitative case study of two high school biology classrooms focused on one curricular unit within the subject of ecology in which two biology teachers co-created an engineering design project. According to those teachers and their constructed materials, the engineering design project where students created water filters was targeting both a life science and an engineering design NGSS performance expectation. This case study included the observation of the enactment of the engineering design project and the engagement in the project in two high school biology classes.

Within the first research question targeting how the teachers incorporated an engineering design project into biology class, themes emerged from the data analysis surrounding how, what, and whom the two teachers planned for. These teachers first selected a specific unit of study in which to incorporate an engineering design project. This selection was based upon their idea of what topic within biology would be the easiest for this integration. This follows Simpson and Whitworth's (2019) idea that ecological engineering is an ideal way to incorporate engineering into the life sciences. They proposed that an appropriate way to include an engineering design project into biology would be to create a project that built upon students previous scientific modeling to support sensemaking about ecosystems. Similar to this, the teachers in this case study selected the engineering design project of designing water filters for the end of a unit on biodiversity as appropriate because biodiversity was considered an easier concept for students. The engineering design project developed by the teachers in this study was different than the proposed project by Simpson and Whitworth as the students in this case study were tasked with building and testing a physical prototype whereas Simpson and Whitworth suggested a written design and solution to a biodiversity problem. The teachers selected the specific NGSS performance expectations of HS-LS2-7 *Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity* and 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* to guide the instruction and assessment of the engineering design project of creating water filters.

Through examination of the teacher-generated materials and the observation of teaching during the project, it became apparent that the focus of the engineering design project was on the process of engineering and not on the learning and or use of specific life science concepts. The instruction given during the project in both classes focused on the specific steps of the given engineering design process students should be working on each day. The presentation rubric written by the teachers as a guide for the student presentations, focused on the process of creating and testing a physical prototype of a water filter with little attention to why a water filter would be needed and no attention to how this could impact biodiversity.

The two teachers who created the student document used in the project emphasized the steps of the engineering design process with specific support of conducting prior online research of the stated problem related to clean drinking water and how to design and build a water filter. Following Silverling et al.'s findings, this emphasis set up teacher-prompted support of evidence-based decision-making during engineering design. According to Silverling et al. (2021), students can engage in the evidence-based decision-making process with only student-directed instructional situations, but they would engage more fully with the inclusion of teacher-prompted instructional situations. One could argue though that the assimilative nature of the student document minimized the opportunity for student-directed instructional situations in which students would engage in an evidence-based decision-making process in the engineering design project. If the goal of the inclusion of this engineering design project was to meet the criteria of engineering standards deemed as a requirement within the science curriculum, Gravel, et al. would argue that this discipline-specific goal lacks commitment to an asset-based learning approach (2021). While both teachers spoke to using what they knew about their students' prior experiences and potential interests and strengths during the initial interview, their asset-based approach to learning science and engineering through this engineering design project was limited. Students were limited to the definitions of student roles provided in the student document created by the teachers. While the stated purpose of the engineering project was to attend to the specific NGSS performance expectation to *analyze a global challenge*, it lacked connection to communities in which students identify. Both Gravel, et al. (2021) and Wilson-Lopez, et al. (2018) argued that engineering challenges need to be authentic in that they focus on problems identified and framed within the students' community. Bob, in the initial interview spoke about previous approaches to incorporating engineering design using a local creek, but that all the possible solutions were already being implemented and that building and testing physical prototypes would be difficult. Students were not asked to make a connection between the global issue of clean drinking water and their community. Students in Bob's class were allowed to choose a location such as Des Moines or Uganda for their water sample, but it was unknown how or why a specific selection was made by a group of students and therefore it is unknown how authentic the engineering project may have been. Using the findings from Wilson-Lopez, et al. (2018) on the mobilization of students' science capital, one could argue that students in this project were not given an adequate opportunity to use their potential social capital. That is, the students had less of an opportunity to interact with others with scientific knowledge or other knowledge relevant to the engineering project. Missing this opportunity may reduce the students' ability to fully engage in an engineering design project and to also apply science-related knowledge and resources to an engineering design problem.

Both Tom and Bob attended to who the students were that would be engaging in the engineering design project in biology both in the design of the project and in their interview responses. As they believed most students were new to the process of engineering design, they made specific choices about what the project would be and how it would be supported both through teacher-generated documents and classroom instruction. Both teachers indicated in the initial interviews that students would be able to use their prior knowledge of water filtering even though the two teachers disagreed with how much prior knowledge students had with this phenomenon. To address their concerns with the students' ability to construct evidence-based decisions and solutions within the engineering design project, the specific research guide was developed by the teachers during the planning of this project for students to use at the beginning of the process of engineering design. Wilson-Lopez et al. (2018) recommended that educators should encourage students to engage in the use of multiple science resources such as accessing Internet sites and using prior knowledge and experiences in conjunction with each other during engineering design as this could also encourage the future activation of other resources. This was considered important as it provided legitimization of differing funds of knowledge and provided practice of the continued use of multiple resources within engineering design to increase student success within the process (Wilson-Lopez, et al., 2018). Both teachers indicated the importance of creating specific student roles within the planning of the engineering project during the initial interviews. Both the teacher-generated student handout and accompanying research guide included descriptions of specific responsibilities within the project by student role within the cooperative groups. The intention of the teachers was to encourage teamwork and allow students to select a role based upon things they do well or are interested in. According to Bob:

> there's roles for the group so there's like an artist who's actually creating the design, there is the engineer that is supposed to be in charge and they're all really working together on this but also maybe this highlights some of those strengths that students have even if they

> don't always get to show every day in their biology class and I could see a different side of students like maybe something that's a strength of theirs they haven't got to shown yet. (Bob, initial interview)

Teamwork is one of the 12 key indicators included in Moore, et al.'s *Framework for Quality K-12 Engineering* (2014), with the argument that the ability of students to participate as a contributing team member is important to engineering. This indicator was reinforced within the engineering design project created by the teachers in this study as students worked as groups with each member having individual responsibilities. Moore, et al. emphasize that all 12 key indicators of the Framework *for Quality K-12 Engineering* taken together, represent quality engineering education. Teamwork is one of the last indicators which means that while it is important for engineering, it is not unique to engineering (Moore et al., 2014). While the creation of individual roles within a cooperative group or team is important to an engineering design project, incorporating this may not be as difficult as incorporating key indicators of engineering such as the processes of design and applying science thinking.

Missing from the incorporation of this engineering design project was the use of science concepts, a finding supported by Singer et al. (2016) in which the Reformed Teaching Observation Protocol (RTOP) was used to illuminate science teachers' struggles to provide opportunities to build science knowledge through engineering. Within the two NGSS performance expectations, the dimension of science and engineering practices described as *design, evaluate, and refine a solution* has more of a presence within both the teacher-generated materials and teacher instruction of the engineering design project. Therefore, this dimension is better-supported within engineering design projects to a greater extent than the other two NGSS dimensions of disciplinary core ideas related to *anthropogenic changes in the environment* and the cross-cutting concept of *stability and change*. The teacher-generated student document and presentation rubric included no information about understanding how to reduce the human impact causing water pollution, and the teacher-generated research document provided little information to students about how human activity changes the environment, or how this affects the stability or change within the environment.

When comparing this to the idea of scientific sensemaking in which students engage in the acquisition of science knowledge, the use of scientific and engineering practices, and the understanding of the nature of science to compose an explanation about a natural phenomenon (Ford, 2012), there were gaps in the students' science sensemaking. When considering whether the engineering design project created by the teachers in this study included science sensemaking, one would need to consider how science knowledge could be acquired and used in the practice of *design, evaluate and refine* from the included NGSS performance expectation related to human impacts on biodiversity. Since this project was created for the end of the unit on biodiversity, one could consider that purpose was not to acquire science knowledge through the project, but to use science knowledge in the engineering design project. Since the NGSS contain engineering design performance expectations separate from the science expectations, this could be viewed as supporting the incorporation or addition of a stand-alone engineering design project versus the integration of engineering into science. Perhaps this is one reason why Singer, et al. (2016) found that science teachers struggled to support students to build science knowledge within engineering design and continued to teach science in isolation of engineering design. Teachers included in Singer et al.'s study participated in professional development intended to support their use of a specific engineering design curriculum within science class. Even with the prescribed curriculum, Singer et al. argued that science teachers lacked the pedagogical content knowledge needed to appropriately integrate science content into an engineering design problem.

According to Moore et al., "students should have the opportunity to apply appropriate science in the context of solving engineering problems" (2014, p. 5). The enactment of the incorporation of engineering design in these two biology classes differed by teacher. Tom's class was taught by Sara, a substitute teacher, during the entire engineering design project. While Bob's class included multiple teacher-prompted situations that led to evidence-based decision-making during engineering design, Tom's class was provided very few of those situations. This was cause for concern as according to Sung and Kelly (2019), those with little previous design experience tend to treat design as the end stage whereas those with more experience view design as a managed, iterative process. Sung and Kelly believed "patterns of design process can help students to cope with the complex nature of design problems by conceptualizing successful pathways to problem-solving" (2019, p. 286). They concluded that iterative design thinking patterns are unique to those engaged in the design and oversimplifying the engineering design process for students can lead to reduced problem-solving ability. If students are going to engage in design as an ongoing process of developing and revising ideas, teachers need to support sketching, predicting, and questioning within the process. While Bob's class included teacher-initiated structure to promote or require these processes, no such structure was observed in Tom's class other than the use of the student document which may have led to less productive problem-solving where students did not learn and practice the iterative nature of design.

The Engagement in Engineering Design in Biology

The second research question targeted how students engaged in the engineering design project and specific themes emerged surrounding the iterative process of engineering design and how students demonstrated learning of both engineering design and Biology. Students in both Tom and Bob's class followed the same teacher-generated student handout throughout the entire engineering project using the same problem to solve and the same guidelines for a final presentation as the assessment of learning during the project. The engagement by students within the iterative process of engineering design differed both between the two classes and by different student groups within Bob's class. The final presentations also differed among groups of students. This was illustrated in Tom's class when one student group began the project by collecting prototype materials and skipped an important part of the prototyping process and the associated scientific testing. The students in Bob's class were prompted to and did follow the engineering steps in sequential order as written on the student handout. The idea is that design is an ongoing process of developing and refining ideas (Sung & Kelly, 2019). While the iterative process of moving from designing, diagramming, building, and testing did occur in both classes, Bob's students were more successful at proposing evidence-based revisions to designs and prototypes using both Internet research and the testing procedures of the water. The student presentations reflected this in two ways. The student groups who engaged in evidence-based revisions were also able to communicate this process. For example, even though the Uganda water group in Tom's class were not successful in completing their prototype or adequately filtering the water, their presentation did reflect a process of considering revisions and why those would be appropriate. This means that those students understood and engaged in the testing and evaluating process as included in the *Framework for Quality K-12 Engineering Education* but did not necessarily engage in engineering thinking as they struggled to troubleshoot solutions and develop new knowledge on their own (Moore, et al., 2014). The India water group in Bob's class was not able to effectively communicate potential revisions to their prototype and those revisions did not address the findings from their final water tests. Even though they engaged in in a similar testing and evaluation process within engineering design, their presentation did not demonstrate engineering thinking.

Students in both classes spent little time engaging in the understanding of science concepts. Within the explanation of the problem, students were introduced to a global problem of access to clean drinking water. Students were to complete Internet research surrounding the specific pollutants in the simulated water sample they chose for the project and current statistics of human illness and death related to unclean drinking water. Students were not able to connect this information to the unit phenomenon or standard-based science concept of biodiversity and human impact on biodiversity. Guzey et al. (2019) argued that a disconnect between the engineering design challenge and science concepts is typical especially when the design challenge is in addition to the science learning versus there being an integrated approach. The students included in this case study engaged in an engineering design activity at the end of the science learning unit in which there was little integration of engineering and science learning. The students were however, engaged in the science practice of *design* included in the project's identified NGSS life science performance expectation. This leads to the question of whether or not students were engaged in scientific sensemaking. As Ford has stated, "whereas scientists tended to make sense of scientific claims by focusing on how data were collected and analyzed to consider what the claims meant, non-scientists were more likely to uncritically relate scientific claims anecdotally to personal experience" (2012, p. 208) when explaining how scientific sensemaking occurs. Students were not asked to explicitly use research or testing results during the engineering design project to explain human impact on biodiversity. According to Guzey et al. (2019), while students enjoy hands-on activities in science such as engineering design, students generally do not make decisions based upon scientific evidence unless specifically encouraged to do so. Students did not engage in discussion of biodiversity impacts or human activities during the engineering project, but instead focused on the process of design. Student group presentations differed in what was presented related to the problem needing a solution. While some student groups in Bob's class communicated what the specific pollutants in the water were, where they came from, and how that might affect human health, other groups in Bob's class and the student group from Tom's class included in this study did not fully communicate the connection between water pollution and human health. The student presentations focused on the process of creating and testing a physical prototype of a water filter with little attention to why a water filter would be needed and no attention to how this could impact biodiversity. Students presented no information about reducing the human impact causing water pollution, how specifically human activity changes the environment, or how this affects the stability or change within the environment.

Connections Between Incorporation of and Engagement in Engineering Design

Looking at the data collected and coded in the formation of themes for each research question, there is a relationship between the two in the findings. The teachers planned for the incorporation of an engineering design project as a means to target the specific NGSS expectations of engineering practices. The students in both Tom and Bob's classes engaged in the process of engineering design during the project. The planning of the engineering design project did not include intentional targeting of the included life science standard related to biodiversity and human impact on biodiversity and students did not engage in purposeful sensemaking of those science concepts in the project. While the teacher-generated materials and student assessment were the same in each class, the classroom instruction during the project was very different between the two classes. The overall effectiveness of student engagement within engineering design reflected the type of classroom instruction given. Sung and Kelly (2019) suggested that mismatched learning and teaching style within engineering design leads to poor student performance. The students in each class were perceived by the teachers to be new to engineering design and thus their level of expertise would reflect an iterative procedural pattern of design thinking which would require specific types of supports. In addition to the differences in engagement in engineering design and the ability to demonstrate learning related to an engineering design project, Haverly, et al. (2020) would argue that the substitute teacher in Tom's class did not provide sensemaking opportunities for students. When referring to sensemaking opportunities, Haverly et al. stated "in equitable science classrooms, peers and teachers view shared ideas as important epistemic resources which afford students epistemic authority" (2020, p. 65). In successful science classrooms, teachers are able to recognize and respond to student knowledge in a way that advances thinking and understanding so that is leveraged by other students and the teacher. Both classrooms of students engaged in a project as groups working together and sharing ideas as was planned by Tom and Bob. Tom's classroom lacked teacher interaction with students within the learning. This meant that sensemaking opportunities were not leveraged by the teacher and therefore may not have occurred or occurred in a limited manner. Bob interacted with students within learning each day of the engineering design project as students worked together and shared ideas as planned. While this teacher-student interaction did include students in the classroom discourse, the teacher did not necessarily leverage students' knowledge within a sensemaking process.

The teachers planned for the use of students' individual assets such as prior learning, experiences, and interests within the engineering design project by developing individual roles within cooperative groups. While the intention of this strategy was to capitalize on students' funds of knowledge and science capital, it was not clear during observations of students if this occurred. Students were all able to work together through multiple steps of an engineering design process and all had success at demonstrating their learning through the presentations. From the student presentations and Bob's feedback to students, it was not clear if the areas of weaker demonstration of learning were due to individual student misunderstandings or misunderstandings related to group engagement in the engineering design process. According to Schenkel, et al (2021), multiple design iterations provide students with opportunities to bring their expertise into engineering design, and teachers foster opportunities for students to do this. Perhaps a weakness in the iterative nature of the design of the engineering project or lack of engagement by students in the iterative process led to the weaker demonstration of learning in specific areas of the student presentations.

Implications

While it has been stated that including engineering design in science is more effective when a project is integrated into a science phenomenon versus creating a stand-alone project, the findings from this study illustrate the difficulty with doing this. While the two teachers in this study believed they created an integrated engineering design project, Bob referred to the project as being its own curricular unit in the initial interview. The findings showed a weakness in addressing the sensemaking of the specific science phenomenon the engineering design project was to address. This illustrates a need to examine what the intentions of incorporating engineering design into science are. If it is to engage students in engineering design to provide them with initial experiences and to gain interest, then an add-on or stand-alone approach to this may be appropriate. One should ask if sensemaking of a science phenomenon can be achieved through the use of engineering design or if the goal of an engineering design task should be to have students use prior sensemaking of a phenomenon to support the design process and engineering sensemaking. If science sensemaking and engineering sensemaking should be reinforcing each other through classroom engineering design tasks, then more work needs to be done.

It has been demonstrated that science teachers struggle to incorporate engineering design into science class. According to Nadelson, et al. (2016), national statistics show over three quarters of life science teachers do not feel comfortable engaging students in engineering design tasks. This most likely leads to reduced effectiveness of engineering design tasks if teachers lack the knowledge of and comfort with design illustrated through reduced engineering talk and noticing and leveraging student resources in an equitable way. This lack of comfort with engaging students in engineering design may stem from a limited understanding of the design process in order to support beginners to the engineering process, the students as their problem-solving and decision-making processes related to design are different than that of more experienced engineers. This is concerning as ineffective incorporation of engineering design into science could lead to students reduced understanding of and interest in engineering and other STEM fields.

Recommendations

It is clear from the literature reviewed in Chapter II that more research on engineering design in the life sciences is needed. There may be several causes for a current lack of research on this subject. One cause could be that fewer teaching resources are available for engineering in life sciences. A second reason which may be caused by the first, could be the lack of confidence teachers have with integrating engineering design into life science classes. A third cause of the limited research concerning engineering in life sciences could be that fewer teachers use engineering design problems in their life science classes which could be a result of the first two reasons for limited research stated above. Science teachers are tasked with aligning curriculum to state and national standards in a way that leverages students' everyday experiences and engages all students in equitable learning opportunities (Chudler & Bergsman, 2016). Added to this is the incorporation of engineering design where teachers feel ill-prepared and struggle to create open-ended design challenges (Malone, et al., 2017). Professional development geared toward the goal of reforming life science curriculum to meet the needs of today's classroom is a must. Professional development opportunities should support teachers' understanding of the engineering design process, how to use engineering talk, and how to create opportunities for students to learn life science concepts through design problems related to their own experiences, community, and interests.

In addition to further research on engineering design in life science, more should be done concerning how students' individual assets are leveraged in engineering design since within the *Framework* and the NGSS there are two major goals for K-12 science education: "(1) educating all students in science and engineering and (2) providing the foundational knowledge for those who will become the scientists, engineers, technologists, and technicians of the future" (NRC, 2012, p. 10). One way to better target these goals would be to provide community-centered problems to address through engineering design as Moore et al. stated when referring to quality engineering education, "students should learn the core elements of engineering design processes and have the opportunity to apply those processes completely in realistic situations" (2014, p. 5). Teachers need to be supported through well-constructed lesson plans that include useful instructional strategies. In additional to professional development targeting asset-based engineering design, preconstructed projects and lessons for teachers to revise and use in their classrooms would be useful. Within these design projects, there should be specific connections to the three dimensions of the NGSS performance expectations. That is, the disciplinary core idea(s) and crosscutting concepts need to be weaved into a project along with the science practices which are generally already included. This could provide more support of students' sensemaking of a science phenomenon through engineering design.

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APPENDIX A: INITIAL EMAIL TO TEACHER

Dear ,

My name is Margaret Parker and I am working on my dissertation within the School of Teaching and Learning at Illinois State University. I would like to learn more about how an engineering project is used in a life science classroom to support science learning. I am looking for a secondary educator that identifies as a biology teacher and teaches life science classes. The identification of a life science class would be determined by your school district's curriculum guide. As part of this research, I will be requesting permission to obtain the following:

- All teacher planning materials for one engineering project that occurs in one life science class taught. These materials can include lesson plans, teacher support and implementation materials, and student copies of materials given during instruction.
- Student work completed during and/or after the engineering project related to the project for multiple students in one life science class.
- Feedback given by the teacher to those students on their work completed during and/or after the engineering project related to the project

In addition to these materials, I am also requesting permission to:

- Observe one class period for the entire duration of the engineering project using Zoom. These observations will be viewed in real-time and recorded for later viewing and further analysis.

Participation in this study will include an initial interview completed prior to the beginning of the selected engineering project and again once the engineering project has been completed and students have received feedback. Both of these interviews will be conducted through Zoom and will be recorded.

Appropriate protocols for the confidentiality of all participants and safe storage and access of all collected materials and recordings will be followed by the researcher.

Additional communication between the classroom teacher and researcher can occur before, during and after the selected engineering project but will not be part of the research. The classroom teacher can choose to end the participation in this research at any time.

Thank you,

Margaret Parker

APPENDIX B: INITIAL AND FINAL INTERVIEW PROTOCOL

INITIAL INTERVIEW Protocol

1. What do you think about engineering as a strategy to support learning in science? Potential follow-up may include prior knowledge/use of engineering, models or steps used
2. How does engineering work in a life science classroom?
3. What challenges do you encounter when using engineering?
4. Do you value using engineering in your life science classroom?
5. How was this project selected/created?
6. What do students already/know or can do related to engineering and the science phenomenon?
7. How are students assessed?
8. What are the next steps after assessment?

Final INTERVIEW Protocol

1. Was the project successful?
2. Potential follow-up to include if the project impacted students' understanding of the science phenomenon? Why or why not?
3. Were students successful?
4. How did you determine success (individually/collectively)? What criteria are used?
   5. How did you determine what feedback was appropriate? How do students understand and use feedback? Next Steps?
   Potential follow-up questions specific to feedback given to individual student work such as…

APPENDIX C: CLASSROOM OBSERVATION PROTOCOL

Observation Protocol

Phenomenon Targeted:

10:40-10:55 **10:55-11:10** **11:10-11:25**	
Explaining Phenomena/Designing Solutions: Making sense of phenomena and/or designing solutions to a problem drive student learning.	
Student questions and prior experiences related to the phenomenon or problem motivate sense-making and/or problem solving.	
The focus of the lesson is to support students in making sense of phenomena and/or designing solutions to problems.	
When engineering is a learning focus, it is integrated with developing disciplinary core ideas from physical, life, and/or earth and space sciences.	

10:40-10:55 **10:55-11:10** **11:10-11:25**
Relevance and Authenticity: Engages students in authentic and meaningful scenarios that reflect the practice of science and engineering as experienced in the real world.

Students experience phenomena or design problems as directly as possible (firsthand or through media representations).	
Includes suggestions for how to connect instruction to the students' home, neighborhood, community and/or culture as appropriate.	
Provides opportunities for students to connect their explanation of a phenomenon and/or their design solution to a problem to questions from their own experience.	

Student Ideas: Provides opportunities for students to express, clarify, justify, interpret, and represent their ideas and to respond to peer and teacher feedback orally and/or in written form as appropriate.

Building Progressions: Identifies and builds on students' prior learning in all three dimensions, including providing the following support to teachers:	
Explicitly identifying prior student learning expected for all three dimensions	
Clearly explaining how the prior	

learning will be built upon	

Field Notes:

Phenomenon Students are Actually Engaged In:

Use different color post-it notes to identify steps/stages of the

Engineering Design Process

- Ask: Identify the Need & Constraints
- Research the Problem
- Imagine: Develop Possible Solutions
- Plan: Select a Promising Solution
- Create: Build a Prototype
- Test and Evaluate Prototype
- Improve: Redesign as Needed

APPENDIX D: NGSS EQUIP RUBRIC

EQuIP Rubric for Lessons & Units: Science

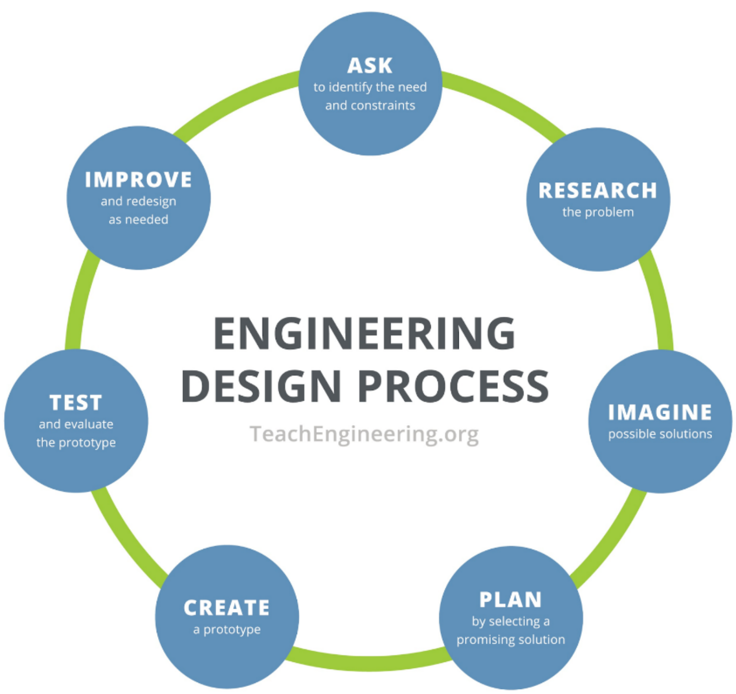
Lessons *and* units designed for the NGSS include clear and compelling evidence of the following*:*

I. NGSS 3D Design	II. NGSS Instructional Supports	III. Monitoring NGSS Student Progress
The lesson/unit is designed so students make sense of phenomena and/or design solutions to problems by engaging in student performances that integrate the three dimensions of the NGSS. A. **Explaining Phenomena/Designing Solutions**: Making sense of phenomena and/or designing solutions to a problem drive student learning. i. Student questions and prior experiences related to the phenomenon or problem motivate sense-making and/or problem solving. ii. The focus of the lesson is to support students in making sense of phenomena and/or designing solutions to problems. iii. When engineering is a learning focus, it is integrated with developing disciplinary core ideas from physical, life, and/or earth and space sciences. B. **Three Dimensions**: Builds understanding of multiple grade-appropriate elements of the science and engineering practices (SEPs), disciplinary core ideas (DCIs), and crosscutting concepts (CCCs) that are deliberately selected to aid student sense-making of phenomena and/or designing of solutions. i. Provides opportunities to *develop and use* specific elements of the SEP(s). ii. Provides opportunities to *develop and use* specific elements of the DCI(s). iii. Provides opportunities to *develop and use* specific elements of the CCC(s).	*The lesson/unit supports three-dimensional teaching and learning for ALL students by placing the lesson in a sequence of learning for all three dimensions and providing support for teachers to engage all students.* A. **Relevance and Authenticity**: Engages students in authentic and meaningful scenarios that reflect the practice of science and engineering as experienced in the real world. i. Students experience phenomena or design problems as directly as possible (firsthand or through media representations). ii. Includes suggestions for how to connect instruction to the students' home, neighborhood, community and/or culture as appropriate. iii. Provides opportunities for students to connect their explanation of a phenomenon and/or their design solution to a problem to questions from their own experience. B. **Student Ideas:** Provides opportunities for students to express, clarify, justify, interpret, and represent their ideas and to respond to peer and teacher feedback orally and/or in written form as appropriate. C. **Building Progressions**: Identifies and builds on students' prior learning <u>in all three dimensions</u>, including providing the following support to teachers: i. Explicitly identifying prior student learning expected for all three dimensions ii. Clearly explaining how the prior learning will be built upon D. **Scientific Accuracy**: Uses scientifically accurate and grade-appropriate scientific information, phenomena, and representations to support students' three-dimensional learning. E. **Differentiated Instruction**: Provides guidance for teachers to support differentiated instruction by including:	*The lesson/unit supports monitoring student progress in all three dimensions of the NGSS as students make sense of phenomena and/or design solutions to problems.* A. **Monitoring 3D student performances**: Elicits direct, observable evidence of three-dimensional learning; students are using practices with core ideas and crosscutting concepts to make sense of phenomena and/or to design solutions. B. **Formative:** Embeds formative assessment processes throughout that evaluate student learning to inform instruction. C. **Scoring guidance**: Includes aligned rubrics and scoring guidelines that provide guidance for interpreting student performance along the three dimensions to support teachers in (a) planning instruction and (b) providing ongoing feedback to students. D. **Unbiased tasks/items**: Assesses student proficiency using methods, vocabulary, representations, and examples that are accessible and unbiased for all students.

C. **Integrating the Three Dimensions:** Student sense-making of phenomena and/or designing of solutions requires student performances that integrate elements of the SEPs, CCCs, and DCIs.	i. Supportive ways to access instruction, including appropriate linguistic, visual, and kinesthetic engagement opportunities that are essential for effective science and engineering learning and particularly beneficial for multilingual learners and students with disabilities. ii. Extra support (e.g., phenomena, representations, tasks) for students who are struggling to meet the targeted expectations. iii. Extensions for students with high interest or who have already met the performance expectations to develop deeper understanding of the practices, disciplinary core ideas, and crosscutting concepts.	
D. **Unit Coherence**: Lessons fit together to target a set of performance expectations. i. Each lesson builds on prior lessons by addressing questions raised in those lessons, cultivating new questions that build on what students figured out, or cultivating new questions from related phenomena, problems, and prior student experiences. ii. The lessons help students develop toward proficiency in a targeted set of performance expectations. E. **Multiple Science Domains**: *When appropriate*, links are made across the science domains of life science, physical science and Earth and space science. i. Disciplinary core ideas from different disciplines are used together to explain phenomena. ii. The usefulness of crosscutting concepts to make sense of phenomena or design solutions to problems *across science domains* is highlighted. F. **Math and ELA:** Provides grade-appropriate connection(s) to the Common Core State Standards in Mathematics and/or English Language Arts & Literacy in History/Social Studies, Science and Technical Subjects.	F. **Teacher Support for Unit Coherence:** Supports teachers in facilitating coherent student learning experiences over time by: i. Providing strategies for linking student engagement across lessons (e.g. cultivating new student questions at the end of a lesson in a way that leads to future lessons, helping students connect related problems and phenomena across lessons, etc.). ii. Providing strategies for ensuring student sense-making and/or problem-solving is linked to learning in all three dimensions. G. **Scaffolded differentiation over time**: Provides supports to help students engage in the practices as needed and gradually adjusts supports over time so that students are increasingly responsible for making sense of phenomena and/or designing solutions to problems.	E. **Coherent Assessment system:** Includes pre-, formative, summative, and self-assessment measures that assess three-dimensional learning. F. **Opportunity to learn**: Provides multiple opportunities for students to demonstrate performance of practices connected with their understanding of disciplinary core ideas and crosscutting concepts and receive feedback.

The Clean Water Initiative

Scenario: Access to clean water is problematic world wide. An estimated 2.2 billion people need access to safely managed drinking water, including 884 million currently without basic drinking water services. An estimated 4.2 billion people need access to safely managed sanitation. An estimated 3 billion people need access to basic handwashing facilities.(Global Wash Fast Facts) You work at a water filtration plant, and your team has been tasked with coming up with a new water filtration system that could be used in areas of the world that don't have access to clean water or solutions. Your filter will need to be made of basic items that are cheap and affordable as many of the areas do not have access to expensive items. You will also have limited time to make the filtration device as it is of the utmost importance that people get access to the filtration device as soon as possible. You will be assigned a sample of water from a specific area of the world. All samples will have organic material and plastic pollution. However, you will need to research the body of water to determine one other prevalent pollutant. You will complete research, design, build, and test a prototype to clean the sample of water. So depending on the issues you find with that water, your filter might look different than others.



Follow the engineering design process to build a successful filtration system. As you work through this project the design process will be broken down into steps. You will complete all tasks as a team, however each of your group members will have a specific role that they are responsible for in the final presentation.

Descriptions of the Roles: Each student will have a role in this project. All group members will assist each other in each aspect, but if a part of the project is not completed in class, whoever is in charge of that part will be responsible for completing it outside of class. Here are the roles and descriptions, please put the name of the group member that will be responsible for each role in the chart.

Role: Description	Name of Student
Member 1: Project Manager: This person will be the head communicator for the group. They will be responsible for identifying criteria and constraints. They will also be responsible for making sure that all criteria are met for the prototype.	
Member 2: Design Tech: This person should be artistic and detail oriented as they will be responsible for overseeing the design or blueprint of the filtration system prototype.	
Member 3: Engineer: This person will be responsible for overseeing the building of the actual prototype.	
Member 4: Scientist: This person will be responsible for overseeing the testing of the prototype. They will record the effectiveness of the prototype and identify areas to improve.	

STEP 1: ASK:
What problem are you trying to solve:

Each group will receive a small canister of water that is from a water source from the following places:

Uganda
Chicago, Illinois
Syria
Bangladesh
Mississippi River Basin
Des Moines, Iowa
New York, New York
India

STEP 2: **RESEARCH**- (see in google classroom)

- Once you have identified the type of pollution present in your area's water source and how to test for this type of pollution, please complete a test to determine the level of pollution. Place the data in the table at step 6.

Step 3: IMAGINE/PLAN: Now that you have researched the body of water and effective filtration systems. Take a minute to identify criteria and constraints. ***Criteria*** *is what the design needs to be able to do, the purpose.Be specific to your body of water, via your research, what should you be filtering.* ***Constraints*** *are limitations to the design.*

Criteria	Constraints

Available Materials and Prices: Keep price under $15

Bottles- free Mesh- $ 1.00 Funnel- $ 2.00 Ring Stand- $ 10.00 Glass Beaker- $ 6.00 Coffee Filter- $ .50/10 filters Cotton Balls- $ 1.00/20 cotton balls	Clay- free Soil- free Rocks/pebbles- free Charcoal- free Sand- free hot plate- free Light- free

Design: Please include your drawing or model of your design below. Annotate each item being utilized and what it will filter or its purpose.

Cost Analysis:

Final Cost_________

Step 5: CREATE Prototype: Now that you have designed a filtration device, you will need to build it.

Step 6: TEST your prototype: Now test your prototype. To get conclusive results you will need to test the water before filtration and after filtration to determine if your prototype is successful.

1. **Initial Test:** First record what the water smells and looks like. Then test for the pollutants in your assigned body of water.
2. **Final Test:** Now pour the polluted water through your filter.
3. Record what the water looks like, smells like, and if the pollutant was removed.

How can you test for the pollutants?

- Nitrogen Levels: Nitrate strips
- Phosphorus Levels: Phosphate strips
- Acidity: pH strips
- Soap and Detergent: pH strips
- Human/Animal Waste or Sewage: Coliform Bacteria Test

Safe levels of pollutants: Reference to see if your levels are safe to drink after filtration.

Indicator	Safe levels **(Note: 1 ppm = 1 mg/L)**
pH	Between 6.5 and 8.5
Nitrogen levels	Less than 10 ppm, ideally under 4 ppm
Phosphorus levels	Less than .03 ppm
Coliform bacteria	none present

Data Table: Water Tests Before and After Filtration

Tests	**Before Filtration System**	**After Filtration System**	**Ideal Water Conditions**	**Is Your Final Filtered Water Safe to Drink Based on Results**
Smell				

Description of what water looks like (before and after pics are helpful here to see water clarity changes)				
Identify the Pollutants here: ____________ ____________ How much of the pollutant was found? (level)				

Step 7: Improve: Now that you have tested your prototype, identify what went well and what could be improved, reference the results to justify improvements.

1. What was successful with your design, provide justification using the data collected.

2. What needs to be improved in your design, provide justification using the data collected.

3. How would you change the design to include the improvements? Draw a new design with the improvements. Remember to annotate the design to include labels of the materials utilized, what they filter, and specifically highlight the improvements in this new design.

FINAL PRESENTATION:

Create a presentation. The purpose of the presentation is to explain the criteria for your filtration system, show the filtration system designed, how you expected it to work, the effectiveness of the system, constraints when building the system, and how you would change it for the future. The criteria for the presentation can be found in the rubric below. It is color coded to help you complete your role.

Note: The visual aid can be a Google Slides, poster, Canva, Venngage, etc.

Rubric:

<table>
<tr><td colspan="2">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.</td></tr>
<tr><td>Criteria</td><td>4
Score</td></tr>
<tr><td>Defining the Problem:The essential problem calling for an engineering solution was clearly described, giving reasons for its significance and consequences if it remains unsolved.
• Clearly identifies overall problem
• Clearly describes significance if it remains unsolved
• Research is referenced</td><td></td></tr>
<tr><td>Criteria and Constraints: Key criteria and constraints were described.
Criteria:
• Correctly identifies problematic pollutants that must be filtered
    • includes evidence statements from research
• Identifies widely available materials
Constraints:</td><td></td></tr>
</table>

• Identifies and describes two key constraints for the solution	
Developing Engineering Solutions Multiple filtration methods were considered. These solutions were refined using research and experimentation. A leading solution was selected using the criteria identified earlier. • A clear/neat prototype blueprint was developed • Components of the filtration device were clearly identified • Purpose of components were explained referencing research	
Prototyping: There is a prototype that essentially meets the goals of the intended design. • A prototype was created following the design • It is durable and could complete all testing	
Testing and Evaluating: The prototype was tested to determine the effectiveness of the proposed solution. Test results were analyzed and used to identify strengths and weaknesses of the proposed solution in terms of project constraints and criteria. • 3 tests were completed and recorded for the effectiveness of the filtration device • strengths were identified and justified referencing data collected • weaknesses were identified and justified referencing data collected	
Revising: Revisions were discussed to address shortcomings in the design. • New design was created • Research is referenced to determine effective changes • Changes are highlighted referencing the data from experimentation.	

Level 5: Remake the filtration device with the new changes and test it to determine the effectiveness of the new model. Create a one pager that includes the items in the above rubric to show the success of the redesign.

Water Filter Engineering Research Guide

Overall Impact of Water Quality and Importance:

WHO/CDC: Outlines importance of safe drinking water and provides stats: - https://www.who.int/news-room/fact-sheets/detail/drinking-water

- https://www.cdc.gov/healthywater/global/wash_statistics.html#:~:text=An%20estimated%202.2%20billion%20people,access%20to%20basic%20handwashing%20facilities.

Filtration Device Sources- How to build:

Here are some starting resources, you may do your own research as well.

How to filter out...	Sources
General Filtration Device Designs:	https://www.itsoverflowing.com/diy-water-filter/ https://www.h2odistributors.com/pages/info/how-to-make-a-water-filter.asp https://www.waterfilteradvisor.com/how-to-make-charcoal-sand-water-purifier-at-home-science-project-diy/ https://tappwater.co/en/what-activated-carbon-filters-remove/
Nitrogen	**https://tappwater.co/en/what-activated-carbon-filters-remove/**
Phosphorus	**https://tappwater.co/en/what-activated-carbon-filters-remove/**
Human/Animal Waste	**https://www.h2odistributors.com/pages/info/how-to-make-a-water-filter.asp**
Acidity	**https://www.hunker.com/13404868/is-clay-soil-acidic**
Soap Detergent	**http://www.reuk.co.uk/wordpress/water/sand-filters-for-greywater/**

Oil	https://sciencing.com/adding-soap-oil-water-7408600.html

Body of Water Sources-

Body of Water	Sources
Uganda	https://borgenproject.org/the-issue-of-water-quality-in-uganda/ https://ugandabiodiversityfund.org/why-uganda-should-ban-plastic-bags/#:~:text=Currently%2C%20it's%20estimated%20that%20at,them%20are%20disposed%20of%20irresponsibly.&text=Plastic%20bags%20are%20also%20the,causing%20threats%20to%20aquatic%20life.
Chicago	https://www.chicagotribune.com/news/ct-xpm-2007-04-04-0704030813-story.html https://chicago.suntimes.com/2021/7/5/22560914/drinking-water-plastic-letters-scott-waguespack-cook-county-property-taxes-exemptions
India	https://www.downtoearth.org.in/interviews/detergents-threaten-indias-waterbodies-16470 https://www.downtoearth.org.in/blog/water/how-our-detergent-footprint-is-polluting-aquatic-ecosystems-77935 https://savethewater.org/organic-pollution-in-india/
Bangladesh	https://www.deccanherald.com/city/life-in-bengaluru/bengalureans-leading-the-way-in-tackling-water-crisis-736629.html https://bengaluru.citizenmatters.in/towards-water-security-how-to-set-up-a-greywater-treatment-system-35327 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6684462/

Mississippi River Basin	https://www.epa.gov/sites/default/files/2015-03/documents/epa-marb-fact-sheet-112911_508.pdf https://www.arcgis.com/apps/Cascade/index.html?appid=3b88aa4466dc4cb5844ba9ffd394e709 https://www.startribune.com/what-pollutes-the-urban-mississipp-lawns-dogs-and-lots-of-pavement/417995413/
Des Moines	https://www.npr.org/sections/thesalt/2013/07/09/199095108/Whats-In-The-Water-Searching-Midwest-Streams-For-Crop-Runoff https://www.desmoinesregister.com/story/money/agriculture/2016/09/29/elevated-nitrates-linked-cancers-birth-defects-environmental-group-says/91228894/ https://www.desmoinesregister.com/story/opinion/editorials/2021/04/22/trusting-ag-agriculture-industry-manure-environment-not-working-editorial-iowa-waterways-rivers/7305791002/
New York	https://www.dec.ny.gov/chemical/8418.html https://news.climate.columbia.edu/2017/08/16/new-york-waters-swimming-in-plastics/
Syria	https://apnews.com/article/middle-east-business-syria-environment-and-nature-oil-spills-97a8a15120ccac7ffe2c9e9c8cbcb612 https://water.fanack.com/syria/water-quality/ --Look at Tigris River**

Information Needed	Source	Information Gained from Source

<table>
<tr>
<td>

What is the significance of clean drinking water?
What are the consequences if drinking water is unclean?

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<td>

Criteria: What is the type of pollution in the water and how did it get there, what’s the source?
Describe the location
Constraint: Why is this location in need of a cheaper filter?

</td>
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<td></td>
</tr>
<tr>
<td>

How is the pollutant harmful?
How did it affect the water quality?
What procedure should you use to test the water?(testing materials will be laid out, check procedures and include here)
Use the table in your project document, what are safe levels to drink of your pollutants

</td>
<td></td>
<td>
<table>
<tr><td>Pollutant 1:</td><td>Pollutant 2:</td></tr>
<tr><td>Procedure:</td><td>Procedure:</td></tr>
</table>
</td>
</tr>
</table>

• What are methods that could be used in order to get rid of this pollutant? • Are they affordable? • How successful will this method be?			
• What would the cost of this method be? (Reference Project Document Materials chart)			

APPENDIX G: TEACHER-GENERATED PRESENTATION SLIDES