HEAT TRANSFER CONCEPTIONS USED IN AN ENGINEERING DESIGN-BASED STEM INTEGRATION UNIT: A CASE OF STRUGGLE

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To my parents, Steve and Kim, and siblings, Jared, Sarah, and Bryce,
for their love, support, and encouragement throughout
the winding path of my life's journey

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ABSTRACT

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In the United States, there has been an increased emphasis on science, technology, engineering, and mathematics (STEM), and especially engineering, in pre-college settings. There are several potential benefits of this, including: increasing the quantity and diversity of students who pursue STEM careers, improving all students' technological literacy, and improving student learning in the STEM disciplines. While current standards support the integration of the four STEM disciplines in pre-college classrooms, research still needs to be done to determine which models of STEM integration are effective and how and why they impact student learning. The context of this study is a model of STEM integration called engineering design-based STEM integration. The purpose of this study was to do an in-depth exploration of students' use of science conceptions during an engineering design-based STEM integration unit, with additional focus on how engineering design, redesign, teamwork, and communication influence students' use of science conceptions. For this study, the unit was designed to address middle school-level physical science concepts related to heat transfer, including temperature, thermal energy, and processes of heat transfer (i.e., conduction, convection, and radiation).

An embedded case study design was used to explore students' science conceptions while they participated in an engineering design STEM integration unit. The case was one student team from a seventh-grade science class, and the students within the team were the embedded sub-units. Data were collected on each day of the unit's implementation; these data included video of the student team and entire classroom, audio of the student team, observations and field notes, and student artifacts, including their engineering notebooks. Data were analyzed primarily using methods from qualitative content analysis. Themes emerged for the whole team, with emphasis on specific students when appropriate.

The results show that there were a few key features of engineering (i.e., engineering design, redesign, teamwork, and communication) that influenced students' use of heat transfer

conceptions. During much of the problem scoping stage, which included the science lessons focused on heat transfer, students mostly used scientific conceptions about conduction, convection, and radiation. However, when they needed to think about those three processes of heat transfer together, as well as apply them to the context of the engineering design challenge, the students began to use a larger mix of scientific conceptions and alternative conceptions. Several alternative conceptions emerged when they combined ideas and vocabulary from conduction and radiation to create one set of rules about thermal properties of materials (i.e., did not distinguish between conduction and radiation). Even when they used scientific conceptions, the students sometimes applied the conceptions unscientifically when designing, which led them to create a prototype that performed poorly. However, the student team then learned from the failures of their first design and redesigned, during which they appropriately used mostly scientific conceptions. In other words, the opportunity to learn from failure and redesign was critical to this team's use of correct conceptions about heat transfer. Two other features of engineering that emerged were teamwork and communication through notebooks. Students on the team learned from each other, but they learned both scientific and alternative conceptions from each other and from their peers on other teams. Engineering notebooks proved to be somewhat helpful to students, since they referred to them a few times when designing, but more importantly they were helpful in revealing students' conceptions, especially for one student on the team who rarely spoke.

The findings of this study contribute to future development and implementation of other engineering design-based STEM integration curricula because they show how various features of engineering influenced this student team's use of science conceptions. In particular, the results demonstrate the importance of giving students the opportunity to learn from failure and redesign, since this process can help students use more scientific conceptions and potentially repair their alternative conceptions. Additionally, it is important for curriculum developers and teachers to think carefully about the transition from problem scoping to solution generation and how to include effective scaffolds for students to help them combine their conceptions from science lessons and apply them correctly when designing. These results also have implications related to heat transfer conceptions, as the student team in this study demonstrated some scientific and alternative conceptions that were already in the literature. Additionally, they used alternative conceptions when they confused concepts from conduction and radiation, which are not in literature about pre-college heat transfer conceptions. These findings suggest that more research should be done to explore the interaction of engineering design and students' science conceptions, especially heat transfer conceptions.

CHAPTER 1. INTRODUCTION

1.1 Rationale

Over the past 20 years, there has been a call for the United States to increase its focus on science, technology, engineering and mathematics (STEM) education in pre-college education, with pre-college engineering receiving more attention over the past decade (Sneider & Purzer, 2014). One goal of this STEM focus in pre-college education is to increase the number and diversity of students who pursue engineering or other STEM careers (Brophy, Klein, Portsmore, & Rogers, 2008; National Academy of Engineering [NAE] & National Research Council [NRC], 2009; NRC, 2012). The U.S. needs more STEM professionals in order to remain competitive in an increasingly globalized economy (National Academy of Sciences [NAS], NAE, & Institute of Medicine, 2007). Additionally, an increased quantity and diversity of STEM professionals are needed to tackle many 21st century problems such as climate change and sustainability (NAS et al., 2007). One thought is that by introducing students to engineering in pre-college settings, they may gain a knowledge of the work of engineers and an appreciation for the ways in which engineers contribute to the improvement of humanity, including economic development, health, and general quality of life (NAE, 2002; NAE & NRC, 2009). By understanding a holistic view of engineering, students may become more interested in it as a career. This is especially important in middle school, which is the setting of this study. Several studies have shown that middle school is a crucial time regarding participation in science and mathematics; these years are when students, especially women and minorities, tend to lose motivation and interest in STEM fields as subjects and future careers (e.g., Cummings & Taebel, 1980; Osborne, Simon, & Collins, 2003). Ganesh and Schnittka (2014) argue that middle school settings are an ideal setting for engineering design and learning because their potential positive effects could counter this loss of interest. Hence, by introducing students to engineering before college, especially during middle school, a greater number and variety of them could be enticed to pursue engineering and other STEM careers.

An additional goal of pre-college STEM education is to improve technological literacy and skills of all students, regardless of whether they choose STEM professions. In our technology-dependent modern society, technological literacy is crucial (Brophy et al., 2008; NAE & NRC, 2014; NAE, 2002). Pre-college engineering and STEM education has the potential to improve students' knowledge about technology and also their ability to make decisions relating to technology, including everyday decisions and those related to public policy (NRC, 2012). Additionally, participating in hands-on STEM activities, especially engineering design projects, can help students develop skills that are useful in everyday life, such as spatial reasoning, general problem-solving strategies, critical thinking, and collaboration (Brophy et al., 2008; NAE & NRC, 2009; Purzer, Strobel, & Cardella, 2014). Thus, learning about the content and practices of STEM in pre-college settings can help all students develop technological literacy and other skills that will be useful to them.

Another potential benefit of learning about and doing engineering and STEM in pre-college settings is the improvement of student learning of STEM concepts and practices. For STEM integration in general, it is thought that having students make connections between the disciplines of STEM will deepen their understand of each discipline and also promote the learning of high-level, integrated skills and knowledge (Czerniak & Johnson, 2015; NAE & NRC, 2014). For engineering specifically, the connection to real-world issues can increase motivation for students to learn science and mathematics concepts since they need to apply them during engineering design challenges (NAE & NRC, 2009; NRC, 2012; Purzer et al., 2014).

Because of these reasons explained above, there has been a national movement to increase STEM education in pre-college settings. Evidence of this can be seen in state and national policy such as K-12 standards, which influence what gets taught in pre-college classrooms (Brophy et al., 2008). While various science and mathematics standards have existed for decades, more recent state and national science standards emphasize integration. As of 2013, 36 states had included engineering in their science standards, either explicitly or implicitly (Moore, Tank, Glancy, & Kersten, 2015). The most recent national science standards, the *Next Generation Science Standards* (NGSS), include STEM integration in multiple ways (NGSS Lead States, 2013). Based upon the national report *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012), NGSS is made up of three major components: scientific and engineering practices, crosscutting concepts, and disciplinary core ideas. One way STEM integration is visible in this report is that engineering practices are included alongside science practices. Additionally, there are four disciplinary core ideas, or areas of content knowledge: earth and space science; life science; physical science; and engineering, technology, and applications of science (NRC, 2012). In short, engineering is explicitly integrated with science in the practices and disciplinary core ideas of NGSS (NRC, 2012). Another way in which the national science standards include STEM integration is their ties with mathematics. Each performance expectation (i.e., standard) in NGSS has explicit links to the national mathematics standards, Common Core State Standards: Mathematics (CCSSM; National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010). In sum, while they are science standards in name, the NGSS encourage learning of all four STEM disciplines (NRC, 2012; NGSS Lead States, 2013).

While standards have described learning outcomes for the STEM disciplines, the methods by which the STEM disciplines are taught in schools and classrooms vary (NAE & NRC, 2014). Bybee (2013) described nine models of "STEM integration" that are currently used in classrooms. Several of these models do not include all four disciplines of STEM (e.g., "STEM" as a reference for science and mathematics only). Other models include all disciplines but not in an integrated manner; consideration of the disciplines as separate is often called "siloed" disciplines and is the traditional class structure for middle and high school education. Models that involve some level of integration across all four STEM disciplines are included in the nine types, but they are rarer. Therefore, as STEM integration becomes more common in pre-college classrooms, there is a need to study the different models of STEM integration is order to determine in which contexts, as well as why and how, various models function.

1.2 Problem Statement and Research Questions

One of the ways to integrate the STEM disciplines is to have students participate in an engineering design challenge, through which they learn science and mathematics concepts and practices as they create a technology; this is often called *design-based learning* (e.g., Apedoe, Reynolds, Ellefson, & Schunn, 2008). For this study, this model of STEM integration is called *engineering design-based STEM integration*. An advantage of this model is that it is designed to integrate engineering into existing science and mathematics courses, rather than making it a course on its own. Some research has been done about the effect of *design-based* curricular units and activities on student learning of science, engineering, and/or mathematics (e.g., Kolodner et al., 2003). However, most of these studies evaluate the students' knowledge before and after the unit, without an in-depth analysis of the conceptions they use during the design-based experience. Without studies that follow the students as they participate in and learn from design-based units, it is difficult to identify how specific features of engineering design-based STEM integration influence student science learning. In this study, the features of engineering explored are engineering design, redesign, teamwork, and communication. Discovering more about how these features influence students' use of science conceptions would be valuable to the development and implementation of future design-based curricula.

Thus, the purpose of this study is to do an in-depth exploration of students' use of science conceptions during an engineering design-based STEM integration unit, with specific focus on how certain features of engineering influence their use of scientific or alternative conceptions. For this study, the unit is designed to address middle school-level physical science concepts related to heat transfer, including temperature, thermal energy, heat, and processes of heat transfer (i.e., conduction, convection, and radiation). Heat transfer concepts are commonly considered important for middle school students to learn, as they are consistently in science standards (e.g., NGSS Lead States, 2013). Additionally, heat transfer is a science content area that has been frequently used in engineering design-based STEM integration curricula, usually with positive effects on science learning (e.g., Goldstein, Omar, Purzer, & Adams, 2018; Schnittka & Bell, 2011). However, as with other literature, less work has been done to deeply explore how and when students use heat transfer conceptions as they participate in an engineering design process.

Therefore, the following research questions guided this study:

- During an engineering design-based STEM integration unit:
    - What scientific and alternative conceptions about heat transfer does a team of middle school students use?
    - How do engineering design, redesign, teamwork, and communication influence students' use of these conceptions?

1.3 Potential Significance

The outcomes of this research could have implications for researchers, curriculum developers, and teachers in engineering education, science education, and STEM integration education. For engineering education, discovering how different features of engineering (i.e., engineering design, redesign, teamwork, communication) influence students' use of science conceptions could impact how design-based curricula are designed and implemented in the future. For science education, revealing which heat transfer conceptions students use during an engineering design-based STEM integration unit, as well as how they use them, will add to research and practice about heat transfer alternative conceptions and how well different interventions help students develop scientific conceptions. With engineering and science education combined, this study can more broadly inform how STEM integration can be used to support learning in multiple disciplines.

1.4 Overview of the Following Chapters

This section provides an overview of the remainder of this dissertation. Chapter 2: Literature Review and Conceptual Framework provides additional background information for this study. This includes a review of the research literature that explores design-based learning and conceptions about heat transfer in pre-college science and engineering education, as well as a description of the conceptual framework that guides the larger research project within which this study is situated and acts as a lens for the analysis in the current research study. The literature review and conceptual framework provide additional justification for the research questions.

Chapter 3: Methods contains detailed information about the research design of the study. This includes explanations about the research design, data collection, and analysis. Additionally, it is in this chapter that there are in-depth explanations of the larger project, the engineering design-based STEM integration curricular unit used for this study, and the study's setting and participants.

In Chapter 4: Results: The Case, detailed results are described. The chapter begins with an overview of the results, which shows what scientific and alternative conceptions about heat transfer students demonstrated in each step of an engineering design process. The bulk of this chapter is a detailed case which describes students' use of heat transfer conceptions in each lesson of the engineering design-based STEM integration unit. The chapter also provides an analysis of students' use of key terms, such as "heat," as well as additional information about one student's participation in the curriculum.

In Chapter 5: Summary of Results and Discussion, the results from the case are summarized and organized by components from the conceptual framework. These results are also compared and contrasted to results of other pre-college engineering education and science education studies.

Chapter 6: Implications for Research and Practice provides concluding remarks about the study. Implications for the specific curricular unit and more generally for researchers, curriculum developers, and teachers are provided. Potential future research directions are also recommended.

CHAPTER 2. LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

This section describes additional literature that is relevant background for this study. As a reminder, the research questions are:

- During an engineering design-based STEM integration unit:
    - What scientific and alternative conceptions about heat transfer does a team of middle school students use?
    - How do engineering design, redesign, teamwork, and communication influence students' use of these conceptions?

First, there is a literature review with more information about design-based learning and heat transfer conceptions in pre-college education. Second, the STEM Integration Framework, which is the conceptual framework of the study, is described.

2.1 Design-Based Learning/Science/STEM Integration

In one type of STEM integration, engineering design challenges are the overall foundation and context of curricula; by participating in an engineering design process, students are meant to achieve learning goals related to science and/or mathematics as they apply these content and practices to their design solution. This type of integration has been called *design-based learning* (e.g., Apedoe, Reynolds, Ellefson, & Schunn, 2008; Mehalik, Doppelt, & Schunn, 2008), *design-based science* (e.g., Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Schnittka & Bell, 2011), *STEM-design challenges* (Berland et al., 2013), *Learning by Design* (LBD; Hmelo, Holton, & Kolodner, 2000; Kolodner et al., 2003; Puntambekar & Kolodner, 2005), and *(engineering) design-based STEM integration* (e.g., Guzey, Harwell, Moreno, Peralta, & Moore, 2017; Guzey, Moore, & Harwell, 2016; Mathis, Siverling, Moore, Douglas, & Guzey, 2018). The engineering design-based STEM integration curriculum that was implemented as a part of this study falls into this category, so it is important to consider the effect of similar curricula on student learning and communication about science content and practices. For the purposes of this section of the literature review, studies have been limited to those focusing on science learning through design-based curricula in middle and high school classroom settings because the students who are the focus of this study are in seventh grade, making other research about secondary (i.e., middle and high school) settings most relevant.

The organization of the *design-based learning/science/STEM integration* section is as follows. I first describe how engineering design-based STEM integration has been integrated with various topics and disciplines of science. In the second part of this section, I review outcomes about student learning of science content and practices through their participation in design-based units, including outcomes about specific populations of students. This section establishes that students who participate in design-based curricula are able to learn science as well or better than their peers in more traditional science classrooms. In the third section, I review literature about students' communication (spoken and written) of science and other topics during engineering design-based units.

2.1.1 Science Discipline Focus in Design-Based Curricula

Engineering design-based STEM integration curricula have been used to support middle and high school student learning of a variety of topics within the three major disciplines of K-12 science: physical, earth, and life. Physical science is the science discipline most commonly used in design-based curricula, with studies focusing on heat transfer and thermal energy (Apedoe et al., 2008; Guzey & Aranda, 2017; Schnittka & Bell, 2011); electricity and circuits (Doppelt, Mehalik, Schunn, Silk, & Krysinski, 2008; Mehalik et al., 2008; Silk, Schunn, & Cary, 2009); force and motion (Cantrell, Pekcan, Itani, & Velasquez-Bryant, 2006; Kolodner et al., 2003); buoyancy and density (Barnett, 2005); electrochemical cells (Fortus et al., 2004); and optics and properties of light (Valtorta & Berland, 2015); to name a few. Earth science-focused curricula also exist but to a lesser extent, with focus topics such as rocks and minerals, the rock cycle, and underground water (Kolodner et al., 2003); and Earth's structures and processes (Kolodner et al., 2003). Some design-based curricula in the literature focus on multiple disciplines, such as identifying and separating mixtures using physical and chemical processes (physical science) to design water purification systems to improve water quality (earth science; Mooney & Laubach, 2002; Riskowski, Todd, Wee, Dark, & Harbor, 2009). Life science-focused, engineering design-based curricula have become more popular in recent literature, including curricula with science content foci of the respiratory system (Hmelo et al., 2000); genes, genetic expression, and how the environment affects cell division (Ellefson, Brinker, Vernacchio, & Schunn, 2008); adaptations and habitats (Siverling, Guzey, & Moore, 2017); ecology and ecosystems (Siverling et al., 2017); and cell structure and function, enzyme activity, and DNA extraction (Mathis et al., 2018). These lists of science topic foci demonstrate the range with which engineering design has been used as a foundation to support learning in the three major science disciplines.

2.1.2 Assessments of Science Learning in Design-Based Curricula

Although engineering design-based STEM integration curricula have been designed to support student learning, it is important to note whether or not they have been successful in that goal throughout implementation of the curricula. A common way to measure science content learning is through quantitative pre- and post-tests, sometimes compared to control classrooms and sometimes not. In the next two sub-sections, I describe science learning outcomes of these pre-post assessments, first the outcomes across the entire population of study (e.g., class, school) and then broken down into specific groups such as gender, race/ethnicity, socioeconomic status, and special needs.

2.1.2.1 General outcomes.

Most of the results of science content learning in the following studies show positive gains. A promising result is that most of the studies showed science content learning gains from pre-unit to post-unit, though the amount, absolute post-test score, and comparison to control classrooms (when available) varied. In most studies that did not have a control group, significant science content knowledge gains occurred for middle (Doppelt et al., 2008; Goldstein et al., 2018) and high school students (Apedoe et al., 2008; Berland et al., 2013; Chao et al., 2017; Ellefson et al., 2008; Fortus et al., 2004; Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005). However, in one study about three teachers' implementations of a life science-focused engineering design-based STEM integration unit, science gains were not significant (Guzey, Moore, Harwell, & Moreno, 2016). Significant science content learning gains were also present in most control-treatment comparison studies. These studies showed the same or larger gains in student science content knowledge learning through design-based curricula than traditional curricula at middle (Hmelo et al., 2000; Kolodner et al., 2003; Mooney & Laubach, 2002; Riskowski et al., 2009; Schnittka & Bell, 2011) and high school levels (Barnett, 2005). For example, in one study of eighth grade classrooms, the design-based learning classes displayed gains about electricity concepts that were twice as large as the traditional classes (Mehalik et al., 2008). In another study, sixth grade students in a design-based learning environment performed significantly better than peers in more traditional science environments on both a true-false test about the respiratory system and a drawing activity where they demonstrated more sophisticated understandings of the structures, relations, and behaviors of human lungs and respiratory system (Hmelo et al., 2000). Again, not all research of this type has found significant science content learning gains. In one large scale study of 4450 students in 59 teachers' classrooms, engineering was found to not be a significant predictor of elementary student science achievement; engineering only favorably predicted middle school science achievement for curricula with a science focus of heat transfer (Guzey et al., 2017). On the whole, these studies suggest that design-based learning curricula are as effective, and sometimes more effective, at increasing students' science content knowledge than traditional science curricula.

Student gains in terms of science practices and skills have also been studied, though to a lesser extent. In one study of eighth graders, two classrooms learning through a design-based curriculum, one classroom using science inquiry, and one textbook-based classroom were compared for gains in science reasoning skills (Silk et al., 2009). The pre-posttest was about controlling variables in experiments and drawing conclusions about relationships among variables from data. Students from all four classrooms showed significant increases in their scientific reasoning skills, but the design-based learning classes had the largest effect size, followed by the inquiry and finally the textbook-based classes. The authors attributed this result to the fact that the design-based curriculum provided students with a rich context in which they could meaningfully use scientific reasoning skills. The middle school LBD curricula have also been analyzed for science practices through the use of performance tasks (Kolodner et al., 2003). Before and after an LBD unit, students were instructed to design, carry out, and analyze data from science experiments unrelated to the LBD curriculum. Analyses of these performance assessments show that LBD students performed consistently better at science reasoning, collaboration, and metacognitive skills than non-LBD students.

2.1.2.2 Outcomes with specific populations.

Several assessments of science learning in engineering design-based STEM integration curricula were also broken down by specific populations of students. These studies show mixed results for every sub-group category.

In terms of gender, larger science content and skills gains have been made by male students (Cantrell et al., 2006; Mehalik et al., 2008) or female students (Kolodner et al., 2003; Riskowski et al., 2009). For example, Kolodner et al. (2003) noted that in Learning by Design curricular units, female students typically scored lower than male students on the science pre-test but did as well or better on the post-test. Through other design-based curricula, male and female students both demonstrated significant growth (Chao et al., 2017; Doppelt et al., 2008; Silk et al., 2009) or both did not (Guzey, Moore, & Harwell, 2016).

For race/ethnicity, results also varied. In one study, significant science gains were made by white students but not non-white students (Riskowski et al., 2009), while another study showed science improvement for Hispanic and African American students but the reverse outcome for white and American Indian students (Cantrell et al., 2006). Through a module focused on science concepts of electricity and circuits, African American students achieved significant science content knowledge growth (Doppelt et al., 2008; Mehalik et al., 2008). In one of these studies, African American students participating in the design-based curriculum had science knowledge gains eight times higher than African American students who learned through scripted inquiry classes (Mehalik et al., 2008). Other studies about design-based curricula showed significant science improvement for all race/ethnicity subgroups (Silk et al., 2009) and for none (Guzey, Moore, Harwell, et al., 2016).

Results for socioeconomic status (SES), usually indicated by students receiving free or reduced-price lunch, have been somewhat consistent. Students with low SES have shown significant science improvement through the implementations of various design-based curricula (Doppelt et al., 2008; Kolodner et al., 2003; Riskowski et al., 2009). In other cases, the science content learning of low SES and high SES students have both shown significant improvement (Silk et al., 2009) and both not (Guzey, Moore, Harwell, et al., 2016).

Students for whom English is a second language (ESL), which is also classified as limited English proficiency (LEP), have rarely been studied in literature about design-based STEM integration. Similar to most other sub-groups in the study, Guzey et al. (2016) found that LEP status was not a significant predictor of score on the unit's life science post-test. On the other hand, Riskowski et al. (2009) found that not only did ESL students in the design-based unit perform significantly better than ESL students using a more traditional science unit, but also that ESL students in the design-based unit had the greatest gains from pre- to post-test of science content knowledge.

Another possible subgroup for whom science learning gains have been studied is special education students. Cantrell et al (2006) found that although special education students performed below the class mean in all post-test measures – the state science exam, a unit-specific exam, design project scores, and interviews with students that tested the same content as the unit-specific exam – they had scores much closer to the mean for the design project score and individual interviews. The authors suggest that this outcome indicates that special education students are learning science content through engineering design, but some measures may be better at demonstrating those gains than others. Silk et al. (2009) came to a similar conclusion based on their analysis of special education students. In a pre-posttest comparison of science reasoning, special education students were the only subgroup studied to not have significant improvements. After an initial multiple regression analysis, the authors found that being designated a special education student was negatively associated with post assessment scores. However, in a second multiple regression analysis that also factored in students' reading level, being designated a special education student was no longer a statistically significant predictor of science post-test scores. The authors concluded that differences in reading ability likely explained at least some of the lower scores of special education students. In Guzey et al.'s (2016) regression analysis of a life science posttest, only one of the subgroup predictors was significant, the subgroup of special education students. In other words, participating in a design-based STEM integration unit had a positive impact on special education students' science posttest scores. These three studies suggest that design-based curricula can be especially helpful for special education student learning of science, but this learning is difficult to measure given typical pre-post measures.

A final way that researchers have broken students up into subgroups is by considering prior test scores or grades. Kolodner et al. (2003) noted that after many implementations of Learning by Design units, the largest gains usually occurred in students with lower pretest scores. For each of the three design-based science units in another study, Fortus et al. (2004) split students into two groups based on who scored above and below the median of the pretest: high achievers and low achievers, respectively. In all three units, low achievers had higher science content knowledge gains than high achievers. Similarly, Mehalik et al. (2008) split students into groups for the pre- and posttest based on whether their science test scores were low (less than 30%), medium (30-60%), and high (above 60%). The authors found that when compared to students learning through a scripted inquiry curriculum, students in the design-based group had more upward shifts from pre- to post-test, especially out of the low group. When analyzed by previous science grade (A-D), Riskowski et al. (2009) found significant science learning gains from pre to post for all grade letter levels except B's; D students had the greatest gains, starting at lower pre-test scores but achieving similar science learning outcomes as other students. In the final study mentioned here, the same curriculum was implemented in two levels of science classes as designated by the school, a low achieving class and a high achieving class (Doppelt et al., 2008). Though the students in the low achieving class showed non-significant growth on the science pre-posttest, they demonstrated noticeable gains in science content knowledge in other forms of data collected for the study (i.e., teacher and researcher reviews of student design teams' oral presentations, analysis of design teams' design portfolios). Because this group was a classroom designated low level by the middle school, the researchers attributed the limited gains of these students to their difficulties in reading the test, not their actual science content knowledge. This conclusion is similar to ones described earlier about special education students (Cantrell et al., 2006; Silk et al., 2009).

2.1.2.3 Summary of assessment outcomes.

In sum, the results of these studies show mostly positive gains in student learning of science content and practices through design-based curricula. In most of the studies, students demonstrated significant gains in science learning outcomes. In addition, in most studies that compared these students to those in more traditional science classrooms, the former performed as well as or better than the latter. When analyzed by a particular subgroup, the results have been more mixed. Different design-based curricula promote science learning of different groups, though there is a general trend that design-based curricula especially help students who are typically low-achieving in science. These initial results are positive, indicating that for the most part, students can learn as much or more science through engineering design as through more traditional instruction. However, what these assessment results are lacking is a deeper understanding of how, why, and/or when students learn science concepts through design-based curricula.

2.1.3 Student Science Communication During Design-Based Curricula

Besides quantitative pre-post assessments, student science learning through and application to engineering design challenges can be observed through their communication during design-based curricula. These communications include small group discussions (e.g., Guzey & Aranda, 2017; Valtorta & Berland, 2015) and written entries into engineering notebooks (e.g., English, Hudson, & Dawes, 2013; Gale, Koval, Ryan, Usselman, & Wind, 2018; Mathis et al., 2018), portfolios (Doppelt et al., 2008), design diaries (Puntambekar & Kolodner, 2005), or electronic notes (Purzer, Goldstein, Adams, Xie, & Nourian, 2015). Additionally, design projects often culminate in a final communication about the design, whether that is a presentation (Doppelt et al., 2008; Hmelo et al., 2000; Puntambekar & Kolodner, 2005) or letter (Gale et al., 2018). In some cases, teachers and/or researchers have also interviewed students after a design-based curricular unit to delve deeper into their learning (Berland et al., 2013; Cantrell et al., 2006; Gale et al., 2018). Exploring students' spoken and written communications during and after design-based curricula reveals more details about their learning and use of science, including when in the design process they tend to use science, what kinds of science they use, and how well they are able apply the science to the design challenge.

Previous studies about pre-college design-based curricula have shown that the science content knowledge that is focus of a unit is not always required in the solution of an engineering challenge (Roehrig, Moore, Wang, & Park, 2012). This can be seen in some implementation results. For example, in one study of four eighth-grade student teams, only one of the groups focused on the science content while the other three mostly talked about the cost of materials and financial feasibility of their designs (Guzey & Aranda, 2017). Notably, the team that focused on science had the best-performing design; however, the other three teams were able to complete testable prototypes. Similarly, a class of ninth-grade students mainly focused on the aesthetics of their remote-operated submarines at the beginning of a design challenge (Barnett, 2005). It was not until one team made a semi-functional prototype that the other teams began to consider the functionality and physics behind their prototypes. During the implementation of a seventh-grade design-based curriculum, a student team discussed some of the science content that was intended to be the science focus of the curriculum (i.e., ecology and ecosystems), but the discussion was limited and very specific to the design context (Siverling et al., 2017). On the other hand, the team applied a lot of physical science related to waterproof-ness and floating since a criterion of the design solution was that it should float in water. On the whole, the student team made many connections between science and their engineering solution, as well as between life science and physical science, but most of their conversations were about science content that was not aligned with the intended science learning outcomes of the unit.

Other research has demonstrated that students sometimes use additional science beyond the focus of the curricula. In one study of seven student teams, one from each of seven different fifth- through eighth-grade engineering design-based STEM integration curricula, the authors found that all seven teams used science that was the intended focus of the unit at least once to justify their engineering design ideas and decisions (Siverling, Suazo-Flores, Mathis, & Moore, submitted). In addition, two teams used science content outside the scope of the curricula to justify their designs; this science was relevant to the design solution, but the topic (i.e., properties of materials) was not in the units' learning outcomes. Similarly, another study of an upper-grade high school classroom showed students using different kinds of science and mathematics in their engineering design solutions (Valtorta & Berland, 2015). In addition to noting that the students used very little science and mathematics during engineering design solution generation, it was also observed that most of what they did use were topics that were familiar to them. These familiar topics (i.e., measurement, some properties of light) were not the intended focus of the unit, but students readily applied them to their pinhole camera designs. However, for the novel topics that were the intended focus (i.e., formulas related to focal length, some properties of light), students had more difficultly applying them to the solution. They were able to do the relevant calculations but then did not know how to use those results in their camera designs. Similarly, in interviews after the completion of two engineering units that included science, high school students were able to identify the science and mathematics concepts that were relevant to the engineering challenges but did not consistently apply them to their design (Berland et al., 2013). When they talked about resolving disagreements with other team members, they said they sometimes used science and mathematics but often used other considerations such as social relationships, wanting to reflect the real world, intuition, and logic.

Other students have had more consistent success in applying the intended science focus of the design-based curriculum to the engineering solution, though not throughout the entire engineering design process. The electronic notes of two highly reflective high school students showed that while they did a design challenge, they often referred to relevant science concepts about seasonal solar path and heat transfer when reasoning about trade-offs (Purzer et al., 2015). However, when the students used the computer program to generate and test ideas for energy efficient solar buildings, there was no explicit evidence of science application. Mathis et al. (2018) found that one team of seventh-grade students were able to apply science and mathematics from all four science and mathematics lesson of the unit when they justified their design ideas and decisions. This application was especially prevalent when students planned their first design, with references to relevant science and mathematics in individual documents and team conversations and documents. However, during the redesign steps, students discussed measurements and data analysis but did not refer core science concepts.

Written documents have also shown mixed levels of science application. In one eighth-grade design-based curriculum, the majority of the 15 participating students used five different science concepts related to simple machines in their engineering notebooks, and a few students also referred to concepts of potential and kinetic energy (English et al., 2013). In a different eighth-grade design-based curriculum, 75% of student teams referred to relevant physics content in their team engineering notebooks, and these notebooks contained almost no irrelevant or incorrect science (Gale et al., 2018). Similarly, in their individual written recommendations to the client, 69% referenced physical science content related to their automatic braking system designs. Most of this content was about friction and which materials decrease friction, but a few students wrote about other concepts such as force, force balance, velocity/speed, acceleration, and energy.

Puntambekar and Kolodner (2005) also worked with eighth-grade students through two iterations of a design-based curriculum that focused on earth science concepts. In the first iteration, students were given Design Diaries with prompts, but they did not have the intended outcomes. Student wrote in their diaries as homework to prepare for the next day, but once they started teamwork in the class, they rarely referred to their diaries. The teams revised their designs through trial and error rather than referring to the science in their diaries, and when they presented their final designs, they struggled to justify them in terms of science content. An analysis of the notebooks showed that in all seven steps of that curriculum’s engineering design process, most written responses showed no scientific thought or very general science only. For the second iteration, the researchers revised the curriculum by adding more specific prompts to the Design Diaries, explicitly including whole class activities for students to refer to their notebooks guided by the teacher, and including several times for students to present and justify their design ideas to the rest of the class. As a result of these changes, many more students included specific science content in their diaries, though some steps in the design process had more students using science (i.e., refined ideas, final solutions, criteria) than others (i.e., problem, questions, initial ideas). The researchers also observed much more science usage during student presentations about their design ideas, both in terms of the presenting students justifying their designs with relevant science and in terms of the other students asking them questions related to science and the design.

Student communication during design-based curricula can also reveal the correctness (or lack thereof) of their science ideas. As stated earlier, high school science students understood formulas about focal length in the sense that they could use them to do calculations, but they did not understand the concepts enough to apply them to the design of pinhole cameras (Valtorta & Berland, 2015). In an interview with one ninth-grade student who designed a remote-operated submarine, he was able to accurately describe the physics of density and buoyancy as they related to the context of his team's prototype, but he became frustrated and confused when asked to solve an abstract problem about density (Barnett, 2005). During the implementation of a sixth-grade Learning by Design unit, most teams' prototypes reflected little application of science (Hmelo et al., 2000). In observations of the classroom, researchers noticed that most students looked for models to copy (from books and then from each other) rather than make connections between the previous science lessons and design challenge. Also, these designs were mostly representational models of human lungs, rather than prototypes that could function as artificial lungs. When presenting their final artificial lung designs, students used science about lung structure to explain their designs but became confused when asked probing questions about behaviors and functions of lungs. The researchers concluded that the challenge of designing an artificial lung was too complex for students to truly be able to apply all of the science, not just structures but also behaviors and functions of the respiratory system. Analyses of one team's student conversations when designing a DNA extraction protocol also revealed incomplete science understandings (Mathis et al., 2018). For example, the team had several discussions about two design ideas for how to reduce the size of their fruit sample, one idea founded on correct ideas about cell structure and surface area and one idea not. During these discussions, the two students in favor of the latter idea made some statements about science "that were correct in isolation, but when combined and in context it is clear that the students did not fully understand the big picture of the science behind the DNA extraction process" (Mathis et al., 2018, p. 438). These two students eventually agreed to use the former idea that was based on correct science, though it was not clear if they did so because their science conceptions changed or because they simply did not want to argue with the other team members anymore. Also, for another step of the DNA extraction protocol, all of the students on the team referred to a previous science lab about enzyme activity, but none of them did so correctly because they did not refer to the full data set. These design-based curricula demonstrate that students are able to learn some science content knowledge, but they may have semi-correct and incomplete understandings of the science.

To summarize, student communications during and immediately after design-based curricula have shown mixed results in terms of how much and how well students apply various science concepts to an engineering design challenge. A limitation of most of these studies is that they analyze student communication during an engineering design process as a whole, rather than exploring how students use science during different steps of a design process. A few studies do this latter exploration (Mathis et al., 2018; Puntambekar & Kolodner, 2005), but not many. Therefore, the study presented here adds to the literature about design-based curricula by exploring students' use of science conceptions during each step of an engineering design process. By using this more detailed approach, it might be possible to identify how specific features of engineering, especially engineering design and redesign, influence student learning of science concepts.

2.2 Design-Based Curricula that Include Heat Transfer Concepts

Several design-based curricula include science concepts about thermal energy and heat transfer, sometimes as the main science focus and other times as a partial science focus. In this section, I describe several of these curricula, including what kinds of design challenges were used to tie to heat transfer concepts and what the results of their implementations were. Here, I include not only design-based curricula that were implemented in middle and high schools but also curricula implemented in elementary schools. This broader range of student grade levels provides a more thorough synthesis of heat transfer-focused, design-based curricula.

2.2.1 Engineering Design Challenges Integrated with Heat Transfer Concepts

A variety of engineering design challenges have been used in heat transfer-focused, design-based curricula. Several of them task students with designing an insulated structure of some kind, whether that is a dwelling for penguins (Schnittka, 2012; Schnittka & Bell, 2011), a habitat for animals (Wendell & Lee, 2010), a greenhouse (Guzey & Aranda, 2017), or a house in extreme environments (Fortus et al., 2004, 2005). In one elementary school curriculum, students are challenged to design an insulated solar oven using the Sun as a renewable energy source (Lachapelle et al., 2011). The Energy3D design simulation, which can be used by middle school, high school, and undergraduate students, also requires students to design a structure (Chao et al., 2017; Goldstein et al., 2018; Purzer et al., 2015). In this computer program, students design energy efficient buildings with solar panels that stay warm in the winter and cool in the summer, which ties to science concepts of sun path and solar insolation, heat transfer, and understanding thermodynamic representations such as solar heat maps and graphs of heat flux. However, the Energy3D design simulation is dependent upon the teacher to emphasize the science concepts. In another secondary school design-based unit, the *Heating/Cooling System* curriculum, students design a system that cools or heats via endo- or exothermic chemical reactions and that meets a need in their own lives (Apedoe et al., 2008). In sum, almost all of these design-based curricular units challenge students to design a product that will minimize or optimize thermal energy transfer, and at the same time, most focus on only one or two of the following: conduction (insulation), convection, or radiation. Therefore, there is an opportunity to explore design-based curricula where the engineering challenge asks students to maximize thermal energy transfer and learn about all three processes of heat transfer: conduction, convection, and radiation.

2.2.2 Assessments of Science Learning in Design-Based Curricula with Heat Transfer Concepts

In pre-post assessments of student science knowledge that mostly focused on science concepts related to thermal energy and heat transfer, studies have shown significant learning gains at the elementary level (Lachapelle et al., 2011; Wendell & Lee, 2010), middle school level (Goldstein et al., 2018; Schnittka & Bell, 2011), and high school level (Apedoe et al., 2008; Chao et al., 2017; Fortus et al., 2004, 2005). In one study of multiple design-based curricula with various science content foci, a regressions analysis revealed the treatment of engineering significantly favored only middle school units with a science focus of heat transfer (Guzey et al., 2017). In other words, doing an engineering design project positively affected student learning of heat transfer concepts, but there was no significant positive effect for other concepts such as ecology, plate tectonics, and particle theory.

In other studies, the extent of the learning gains depended on other factors. For example, when two schools of seventh-grade students used the Energy3D program with an engineering design focus, they both showed significant gains in science content learning related to sun path and solar insolation, heat transfer, and representations (Goldstein et al., 2018). However, one school, Brookside, had significantly higher improvement than the other, Bay. Brookside had explicitly integrated the project by doing it in both science and mathematics classes, had mini-lessons about the content and therefore had explicit instruction, had used more class time, and had students work in teams. In comparison, Bay students worked individually on the Energy 3D project during their science class with little explicit instruction from the teacher. Doing the Energy3D project improved science content knowledge for students in both schools, but Brookside had higher improvement due to their method of implementation.

In another study, Schnittka and Bell (2011) studied three different groups of students: students who participated in an inquiry-based science unit about thermal energy and heat transfer, students who participated in a design-based unit related to heat transfer called *Save the Penguins*, and students who participated in *Save the Penguins* but also the unit included demonstrations designed to specifically target typical alternative conceptions students have about thermal energy and heat transfer. All three groups had statistically significant improvements in their assessments of science content knowledge. However, the group that did *Save the Penguins* with targeted demonstrations showed significantly greater gains than the other two groups of students, with the inquiry-based class and *Save the Penguins* (without targeted demonstrations) class having no significant difference from each other. Here, students learned the science content from a design-based curriculum, but the demonstrations targeting misconceptions made a large impact. In another implementation, *Save the Penguins* was used with a higher level, advanced class and a lower level, standard class that container a number of students with behavioral, learning, and physical disabilities (Schnittka, 2012). Though an analysis of significance was not done, both classes improved on the heat transfer pre-post assessment. However, the advanced class improved more, widening the gap between the higher-level and lower-level classes. The teacher attributed this difference to her own difference in implementation, since she used more teacher-focused pedagogical strategies with the lower-level students and more student-focused pedagogical strategies with the higher-level students. In the implementations of all of these design-based curricula, students learned science content knowledge about heat transfer and thermal energy, but the amount of gains were different for different types of implementation methods.

2.2.3 Student Science Use Before and After Design-Based Curricula with Heat Transfer Concepts: Interviews

In addition to written pre-post assessments, science learning can also be measured by interviewing students before and after an intervention. Interviews allow researchers to probe deeper and gain a better understanding of what science content students have or have not learned as a result of the intervention. I discuss two studies, one of third-grade students and one of eighth-grade students, in this section.

2.2.3.1 Third-grade students, properties of materials.

The first study is a case study of nine third-grade students (Wendell & Lee, 2010). During the design-based unit, students had explored properties of materials and then designed a quiet, stable, and thermally comfortable model house. During the interviews, students were asked to think about how they would design a sturdy stepstool and an insulated animal habitat. During both the pre- and post-interviews, students provided more justifications for their habitat designs than their stepstool designs, *but* fewer of these justifications were accurate and relevant. Similarly, they proposed a greater number of materials tests for the animal habitat design task, but fewer of these were productive and relevant to creating an insulated habitat. It seemed that the students had a better understanding of the design goal of the stepstool, which was sturdiness and strength, but struggled to focus on the thermal properties goal of the animal habitat.

The post-interviews also yielded a disconnect between vocabulary knowledge and the ability to apply that knowledge. Before starting the design, students were asked to define relevant terms; if they could not, they were given the definition before they proceeded with the design task. Of the nine students, two gave an accurate definition of “insulating” but then had a below-average performance on selecting and testing materials for the animal habitat, five could not accurately define “insulating” but had above-average performance, and two could not define “insulating” and had below-average performance. In other words, the students who did the best at selecting and testing materials for an insulated animal habitat could not define a relevant vocabulary term, and the two students who could accurate provide a definition then struggled on applying it.

The authors also scored the interviews and analyzed the results in terms of improvement and how they connected with scores of their engineering notebooks. The interviews were scored for students' use of accurate and relevant science. All mean scores improved, but only the Test Materials task score improved significantly, while the Select Materials and Describe Materials task scores did not. In other words, after participating in the design-based curriculum, students were better able to propose accurate and relevant methods to test materials properties. When compared to their workbook scores, the Wendell and Lee (2010) found that interview score gains were positively correlated with students' workbook scores. Regardless of whether the students' recordings were accurate or not, "those who recorded more in their workbooks learned more" (Wendell & Lee, 2010, p. 592). The study also noted that the last activity in the workbooks may have been a key factor in the students' learning. In this activity, students reflected on their actions and reasoning that led them to make design decisions about their model houses.

2.2.3.2 Eighth-grade students, Save the Penguins.

In the *Save the Penguins* unit, students were tasked with designing an insulated penguin dwelling that minimized thermal energy transfer. In this study, select eighth-grade students were interviewed before and after they participated in two different versions of the design-based curriculum (Schnittka & Bell, 2011). These versions are the design-based curriculum on its own (referred to as the STP class), and the class that did the curriculum and also observed demonstrations meant to address typical misconceptions about thermal energy and heat transfer (referred to as the STP+ class). Additionally, select students from an inquiry-based science unit were interviewed. During the interviews, a researcher asked students probing questions about thermal energy and heat transfer, and then the alternative and true scientific conceptions stated by students were categorized and counted.

During the pre-interviews, all three classes of students stated essentially the same number of alternative conceptions about thermal energy and heat transfer. On average, they stated twice as many alternative conceptions as true scientific conceptions. These alternative conceptions seemed to come from students' everyday lives, such as "dark objects attract heat," "metals trap or absorb cold," and "insulators are warm and metals are cold" (Schnittka & Bell, 2011, pp. 1872-1873).

During the post-interviews, the number of alternative conception utterances decreased for all three classes, but the decrease was much more noticeable for the STP+ and inquiry-based classes than for the STP class. Though the STP+ and inquiry-based classes had essentially the same number of utterances, the inquiry-based class had the same number of types of alternative conceptions during the post-interview as the pre-interview. In other words, the STP+ had the most gains in understanding heat transfer and thermal energy, such as a better understanding of insulators and conductors and that heat transfers from areas of higher temperature to areas of lower temperature. During the post-interview, few students in the STP+ class stated alternative conceptions such as “heat rises” or “cold transfers” (Schnittka & Bell, 2011, pp. 1878). In sum, all three methods of instruction reduced the number and type of alternative conceptions stated by students, but biggest reduction occurred for students that participated in the *Save the Penguins* design-based curriculum that was combined with demonstrations targeted at typical alternative science conceptions.

2.2.4 Student Science Use During Design-Based Curricula with Heat Transfer Concepts

Another way to examine student understanding of thermal energy and heat transfer concepts is through their communication and artifacts during a design-based curriculum. As described earlier, studies have found that students tend to use more heat transfer concepts during design if they interacted with the instructor more (Guzey & Aranda, 2017) and when they considered trade-offs (Purzer et al., 2015). For the first study, the team which had discussed heat transfer concepts the most had the best greenhouse design in the class (Guzey & Aranda, 2017). In the second study, Purzer et al. (2015) noted that by analyzing trade-offs, especially the trade-off of keeping the house warm in the winter and cool in the summer, the students were able to create adequate designs of energy efficient houses. In another study of ninth- and tenth-grade students, Fortus et al. (2004) compared students’ prototypes of houses that would be viable in extreme environments. In the example team described, they noted a distinct improvement, in terms of design and performance, between the prototypes made before and after a lesson about thermal insulation. Before the lesson, the prototype was focused on structure and had no considerations for insulation. After the lesson, the prototype used insulating materials and took into consideration appropriate outside walls colors (i.e., white colors in desert conditions to reflect light and dark colors in arctic conditions to absorb light). However, the prototype did not show evidence that students thought about shading or double pane windows. The prototype made after the thermal insulation lesson also performed better in the insulating test.

Schnittka and Bell (2011) also explored eighth-grade student's conversations and design artifacts during the implementation of the design-based unit *Save the Penguins*, both the STP and STP+ versions. Students in both classes demonstrated basic understandings about radiation and insulation, distinguishing between materials that shade from and reflect radiation and materials that are good insulators. Though both sets of students discussed air being a good insulator, STP+ discussed more scientific conceptions about insulators including that a vacuum is a better insulator than air and that plastic is also a good insulator. Both STP and STP+ students had conversations about how hot air rises from the black floor of the test oven and therefore they needed to seal their penguin dwelling design. Although the STP students talked about reducing conduction to the prototype by raising it off the floor of the test oven (a correct conception), they still stated alternative conceptions about metals as conductors, including that metals keep in coldness or trap, attract, and absorb cold. Meanwhile, most STP+ students applied correct conceptions about metals to their prototype designs, and they often referred to how conductors can take thermal energy away from the human body; this concept was one of the targeted alternative conceptions in the demonstrations. In general, the STP+ students used many more scientific terms while designing than the STP students, and the STP+ students often used these terms when referring to the targeted demonstrations they had observed. Ultimately, 7 of the 12 teams in the STP class had satisfactory prototypes compared to 10 of the 12 teams in the STP+ class.

These studies demonstrate that students are able to apply science content about thermal energy and heat transfer to their engineering design solutions, though not all teams (Guzey & Aranda, 2017) or all relevant science (Fortus et al., 2004; Schnittka & Bell, 2011). Additionally, students can discuss and apply a mix of scientific conceptions and alternative conceptions about thermal energy and heat transfer while they design a solution to an engineering problem, though explicitly addressing these alternative conceptions seems to lessen their use by students (Schnittka & Bell, 2011). Additional work needs to be done to explore more about students' use of thermal energy and heat transfer conceptions during an engineering design process, such as when during a design process students use science conceptions and whether those science conceptions are used correctly or incorrectly when applied to a design.

2.3 Conceptions about Heat Transfer in Education

In order to explore students' use of heat transfer conceptions during an engineering design-based STEM integration unit, it is important to describe what heat transfer conceptions people have. In this section, I first describe some basic ideas about heat transfer and conceptions. Then, I review heat transfer conceptions from the literature. At the end, I explain one of the reasons that heat transfer is an especially problematic content area to teach and learn in science education.

2.3.1 Important Definitions

To understand the work around heat transfer learning and the work of this dissertation, there are definitions that are important to put forth. First, it is necessary to distinguish a "concept" from a "conception" and a "scientific conception" from an "alternative conception." The term "concept" is used to describe an idea that is generally accepted as truth by the scientific community, and the term "conception" is used to describe an idea that an individual person or group of people has in their minds. If a conception matches a concept, then that conception is a "scientific conception." In other words, the idea that a person thinks is true is also accepted by the scientific community to be true. If there is a mismatch, then a conception is an "alternative conception." I prefer the term "alternative conception" to "misconception" because the latter implies than an idea is universally incorrect. I agree with Pushkin (1997) that, "All conceptions are conceptions. Some we find acceptable; others we do not" (p. 666). "Alternative conceptions" means a conception is different from what is agreed upon in the scientific community, but there are usually scientifically acceptable aspects implied in alternative conceptions (Harrison, Grayson, & Treagust, 1999).

Second, it is necessary to define two important theories of heat. From the 17th through early 19th centuries, the dominant theory about heat was the caloric theory (Brush, 1976). In caloric theory, heat is a substance that can be added to or removed from an object. Because heat is considered to be matter, it has properties of matter and is typically thought of as a fluid (Hewson & Hamlyn, 1984). The caloric theory was replaced by the kinetic view, or kinetic molecular theory. In kinetic molecular theory, heat is "the thermal energy transferred, via particle collisions, from a region of high temperature to a region of lower temperature" (Hecht, 1996, p. 568). Heat is thus an extensive quantity and is a process variable (Kesidou & Duit, 1993). Both theories of heat are relevant to the work of this research, since many alternative conceptions about heat transfer stem from the caloric theory, and kinetic theory is the foundation for scientific conceptions about heat transfer.

2.3.2 Conceptions About Heat Transfer

Conceptions about heat transfer include conceptions about heat, temperature, thermal equilibrium, and processes of heat transfer (i.e., conduction, convection, radiation). Scientific and alternative conceptions have been documented for people of many different ages, including early elementary students (Albert, 1978; Paik, Cho, & Go, 2007; Slone, Tredoux, & Bokhorst, 1990), upper elementary and secondary students (Clough & Driver, 1985; Erickson, 1979; Harrison et al., 1999; Laburú & Niaz, 2002; Lewis & Linn, 1994; Slotta, Chi, & Joram, 1995; Wiser & Amin, 2001; Yeo & Zadnik, 2001), undergraduate students (Chiou & Anderson, 2010; Georgiou & Sharma, 2012; Loverude, Kautz, & Heron, 2002; Pathare & Pradhan, 2010; Yeo & Zadnik, 2001), as well as teacher education students (Carlton, 2000), current science teachers (Galili & Lehavi, 2006), and experts (Lewis & Linn, 1994; Slotta et al., 1995). In this section, I focus on conceptions from upper elementary school students and older.

Generally, pre-college students make developmental progress as they age but still use a number of alternative conceptions. In a study of fifth-, seventh-, and ninth-grade students, Erickson (1980) analyzed students' conceptions related to three viewpoints: caloric theory, kinetic molecular theory, and the "children's viewpoint," which was comprised of conceptions discovered in previous interviews (i.e., Erickson, 1979) that were not caloric or kinetic molecular. The author found that caloric theory was the most prevalent viewpoint for all three age groups of students. However, for the middle and least prevalent viewpoints, some students had more kinetic molecular theory viewpoints than children's viewpoints, while others had more children's viewpoints than kinetic molecular theory viewpoints. Similarly, in another study in which 4-13 year-olds were interviewed about a heating activity and a cooling activity, there was a definite developmental progression with age (Slone et al., 1990). The authors created levels of development including Source (i.e., the explanation focused on the source and not the process itself), then Movement (i.e., the explanation focused on heat moving from one body to another but was rudimentary in theory), and finally Transferal (i.e., the explanation referred to heat moving but also explained a process of heat transfer using notions of conduction, convection, radiation, and/or kinetic theory). For heating, Transferal was unfavored in low age groups but most popular with higher age groups, Source was most popular with low age groups but decreased with higher, and Movement was less popular than both but decreased over age. Similar trends were seen for cooling except that Movement slightly increased over age. However, the development was much more obvious for heating than for cooling since for heating, over 80% of older students were in the Transferal level, whereas for cooling, Transferal, Movement, and Source had similar percentages of students. Although there were clear progressions for both, the heating progression was much more noticeable than the cooling progression.

Next, I describe some of the scientific and alternative conceptions from the literature. This is not a comprehensive list; instead, it focuses on conceptions that are most relevant to this study.

2.3.2.1 Heat vs. temperature

Distinguishing between temperature and heat can be difficult for pre-college students. Studies of students of ages 10-13 have expressed alternative conceptions such as heat and temperature are the same (Schnittka & Bell, 2011), temperature is a measure of the mixture of heat and cold inside an object (Erickson, 1979), and temperature represents the level of heat (e.g., one can set the level of heat on an oven with the temperature dial setting; Albert, 1978). Shayer and Wylam (1981) found that 9-13 year-olds expressed three levels of understanding related to heat and temperature. In the first level, heat was associated with its effects (e.g., burning, melting), and temperature was qualitatively associated with hotness. In the second level, students demonstrated the scientific conception that temperature is quantitative, an intensive property of an object, but they still collapsed temperature, amount of substance, and heat into one concept. In the third level, students correctly understood the relationship between these variables, that the amount of heat flow is a function of mass and temperature. Tenth-grade students who had previously received instruction about heat and temperature expressed some of these conceptions also (Kesidou & Duit, 1993). The majority of students talked about temperature being a measured quantity that is the degree of heat in an object, and some students noted that temperature increases are proportional to the amount of heat and inversely proportional to the type of material (i.e., what resists heat transfer). These distinctions between heat and temperature in older students are more scientific, but the idea that temperature is the degree of heat in an object is an alternative conception.

Adults also struggle to distinguish heat from temperature. In a study of teacher education students, Carlton (2000) found that they associated heat with energy of a substance and temperature with measurement, specifically that temperature is a measure of an object's heat. Similarly, high school physics teachers thought of temperature as a measure of the quantity of heat in an object (Galili & Lehavi, 2006). Even practicing scientists can struggle to explain the difference; two of eight scientists interviewed in one study affirmed that the two concepts are not the same but could not explain why (Lewis & Linn, 1994). Although adults had more scientific views of heat and temperature than pre-college students, they still found both to be difficult concepts.

2.3.2.2 Alternative conceptions about heat and cold

Many alternative conceptions about heat have been identified in students and adults, enough so that researchers have developed categories of conceptions about heat. In Wong, Chu, and Yap's (2016) article, *Are Alternative Conceptions Dependent on Researchers' Methodology and Definition?: A Review of Empirical Studies Related to Concepts of Heat*, the authors review 20 empirical studies about the alternative conceptions of heat at various levels, from kindergarten students to university students to science teachers. In doing so, they condensed the alternative conceptions of heat into five categories: "residing in object, ontological category, movement, cause and effect, and condition" (Wong et al., 2016, p. 501). I have used this organization of five categories of common alternative conceptions about heat in this section, though I have also added literature beyond the 20 empirical studies and also included information about conceptions of cold as a substance that moves.

Alternative conceptions in the *residing in object* category are those that consider heat as being part of, or within, a body or system. For example, heat is equated with thermal energy by some physics teachers, who define heat as "internal energy" or "molecular kinetic energy" (Galili & Lehavi, 2006, p. 530). When students and adults describe temperature as a measure of the quantity or degree of heat in an object (e.g., Carlton, 2000; Kesidou & Duit, 1993), they are implicitly using "heat" to mean "thermal energy." Some researchers argue that this alternative conception is developmentally appropriate for middle school students (Arnold & Millar, 1994; Linn & Songer, 1991). They acknowledge that it is scientifically incorrect to use heat to mean both a stored quantity in an object (thermal energy) and a process of energy transfer (heat), but they accept both of these uses as long as students distinguish the concept of heat from the concept of temperature. Another set of alternative conceptions that fall into this *residing in object* category are those that say that metals attract heat, let heat in, or actively pull heat in; these conceptions are fairly common among middle and high school students (Clough & Driver, 1985; Erickson, 1979). Similarly, middle and high school students use the alternative conception that metals attract, hold, and trap cold (Clough & Driver, 1985; Lewis & Linn, 1994; Schnittka & Bell, 2011), so that cold is also seen as *residing in objects*.

I explain the second and third categories together because they are similar. The *ontological* category contains alternative conceptions related to heat as a perception and heat as a substance, and the *movement* category also considers heat to be a substance but includes alternative conceptions of heat as fluid-like (Wong et al., 2016). For heat as a perception, two studies of elementary school students revealed that they thought of heat as hot (Albert, 1978) or heat becoming hot (Wiser & Amin, 2001), which both relate heat to a sensation they experience. Occasionally, students make explicit reference to heat as a substance, for example talking about heat particles (Erickson, 1980). More often, this alternative conception that heat is an entity or form of matter is implied in phrases commonly used by pre-college and sometimes even undergraduate students, such as “heat moves” (Albert, 1978; Chiou & Anderson, 2010; Slotta et al., 1995) and “heat rises” (Clough & Driver, 1985; Erickson, 1979; Schnittka & Bell, 2011). Middle school students also talk about cold as a substance, or entity, that moves (Clough & Driver, 1985; Erickson, 1979; Schnittka & Bell, 2011). For example, a student holding an ice cube in their hand might refer to cold as moving from the ice cube to their hand, rather than the scientific conception that thermal energy transfer from their hand to the ice cube. For the *movement* category, a key word to identify the alternative conception is “flow” (Wong et al., 2016). For example, middle school students talk about heat being as substance like air that flows (Erickson, 1979) and heat flowing like a liquid from object to object (Shayer & Wylam, 1981).

Alternative conceptions within the *cause and effect* category include conceptions about a source of heat or effect of heat (Wong et al., 2016). Several study participants successfully identified a temperature difference as a source or effect of heat, but almost all said this was the only source and effect (Harrison et al., 1999; Kesidou & Duit, 1993; Laburú & Niaz, 2002). The correct conception is that there are two sources and effects of heat: a temperature difference or a phase change. Finally, the *condition* category refers to the conditions in which thermal energy will transfer (Wong et al., 2016). For example, many undergraduate students in a study done by Chiou and Anderson (2010) stated that systems needed to be "in contact" or "being solid" in order for heat transfer to happen. This alternative conception fully disregards the heat transfer mechanism of radiation and somewhat disregards convection.

2.3.2.3 Using the sense of touch: Different temperatures vs. different rates of heat transfer

One science concept that some pre-college students and adults often do not understand is that "different substances feel different because heat travels through them at different rates" (Clough & Driver, 1985, p. 178). When interviewed, the vast majority of middle and high school students state that metal is colder (i.e., has a lower temperature) than plastic, Styrofoam, or wood when both objects have been sitting in the same ambient temperature for a period of time (Clough & Driver, 1985; Lewis & Linn, 1994; Shayer & Wylam, 1981), even though the objects would actually be the same temperature but feel colder because the thermal conductivities of the materials are different. Some students even go as far as to attribute this result to a property of materials, that metals are intrinsically cold and insulators such as wood and plastic are intrinsically warm (Clough & Driver, 1985; Paik et al., 2007; Schnittka & Bell, 2011). Even teacher education students describe temperature as how hot or cold an objects feels (Carlton, 2000). Interestingly, Clough and Driver (1985) found that although almost all students stated that metals have a lower temperature than plastic when comparing two materials at room temperature and two materials that have been left outside during the winter, some students used the correct scientific conception when they explained why metal spoons left in hot water felt hotter than wood and plastic spoons left in the same hot water. This correct use of the concept that metal spoons felt hotter but were actually the same temperature as the wood and plastic spoons when left in the same hot water increased with student age, with 27% of 12 year-olds using the concept, 63% of 14 year-olds, and 83% of 16 year-olds. When nonscientist adults were presented with the "two objects at ambient temperature" problem, 80% said that they were not the same temperature (Lewis & Linn, 1994). However, many of the adults experienced some conflict with the problem, saying that it seemed like the two objects should be the same temperature but that they knew from their senses and experience that the objects are not. One of the adults eventually reasoned through the conflict to arrive at the correct conception that "metals feel cooler because they are good conductors and absorb heat from your hand" (Lewis & Linn, 1994, p. 666); however, most adults instead questioned the accuracy of the thermometers. Thus, this scientific conception can be difficult for students and adults to understand.

2.3.2.4 Conceptions about conductors and insulators

Middle and high school students, as well as nonscientist adults, have demonstrated several alternative conceptions about conductors and insulators. When interviewing eighth-grade students, Lewis and Linn (1994) found that 82% of them used the scientific conception that materials that are good at keeping objects warm are also good at keeping objects cold. However, when they had to specifically answer questions about insulators and conductors, they said, "conductors keep things cold," and, "insulators keep things hot" (Lewis & Linn, 1994, p. 664). The students also said that materials that feel cool to the touch at ambient temperature (e.g., metal, glass) are good for keeping things cold, and materials that feel neutral (e.g., wool, cotton) keep things hot. The nonscientist adults in the study used a similar alternative conception. When asked what materials to place on top of warm or cool objects in order to feel how warm or cool the objects were, most of the adults selected materials that feel cool to place on top of the cool objects and materials that feel neutral to place on top of the warm objects. Another alternative conception common to the students and adults was that aluminum foil is the best material for wrapping a cold object to keep it cold; participants in both groups cited previous experiences with doing so. Both groups also selected wool as best for keeping objects warm because it causes objects to warm (i.e., wool generates heat). This alternative conception about insulators generating heat was also common among eighth-grade students before they participated in the *Save the Penguins* unit (Schnittka & Bell, 2011).

Other studies have shown contrasting alternative conceptions about conductors and insulators. Some students have the alternative conception that "insulators keep cold from transferring" (Schnittka & Bell, 2011, p. 1872), while others explain that because heat and cold flow rapidly through insulators, those materials do not feel hot or cold (Lewis & Linn, 1994). The students in the Lewis and Linn (1994) study also believed that heat and cold flow slowly through conductors, which is why metals feel hot and cold. In contrast, other pre-college students have used the alternative conception that heat is conducted or absorbed by metal so well that when a metal object is place in contact with a hot object, the metal will gain a higher temperature than the initially hot object (Harrison et al., 1999; Paik et al., 2007).

Finally, sometimes experiments can lead students to alternative conceptions about conduction and insulation. For example, Lewis, Stern, and Linn (1993) conducted a study with students in which the students made prediction curves for heating and cooling. For some of the students in the study, the prediction led to confusion about which materials were good insulators. Their results showed that some teams of students made prediction curves that overestimated the level of conduction of a material. When the experimental results showed less conduction than the students' predictions, sometimes they interpreted the results as meaning that the material was a good insulator, rather than that their predictions were poor.

2.3.2.5 Conceptions about radiation

In contrast to the topics of heat, temperature, thermal equilibrium, and conduction, there are very few studies about students' conceptions of radiation in terms of thermal energy. There have been studies about optics and ionizing radiation – especially nuclear radiation – but almost none about thermal radiation (Neumann & Hopf, 2012). Therefore, there is also limited knowledge about students' conceptions of thermal radiation and the effects of materials absorbing, reflecting, and transmitting electromagnetic radiation, or light.

In Neumann and Hopf's (2012) study, they interviewed 14-16 year-olds about their conceptions about radiation. Their conceptions of the term "radiation" varied, and 54% said at least one idea about solar radiation, including the Sun and/or light. However, when asked to comment on pictures of everyday objects, few students included light as a type of radiation. They said that sources of light, such as light bulbs and the Sun, emit light but not radiation. Similarly, when asked if they had heard about different types of electromagnetic radiation (e.g., microwave radiation, UV radiation, nuclear radiation), most students identified most types of radiation, with the exception of visible light. About half of the students were either unfamiliar with or unsure of "visible radiation" (Neumann & Hopf, 2012, p. 830). Finally, when asked if they agreed with the statement, "Every object emits radiation," about a quarter of the students agreed, but only one of the 50 participants justified their response with the concept of thermal radiation. The authors recommend emphasizing to students that light is also a form of radiation.

Schnittka and Bell (2011) identified a few conceptions about how radiation interacts thermally with materials that eighth-grade students had. Before participating in the *Save the Penguins* unit, a common alternative conception was the idea that "dark objects *attract* heat" (Schnittka & Bell, 2011, p. 1881). This conception was also mentioned by some students as they designed insulated penguin-shaped ice cube dwellings that were to be placed in a hot environment. Most teams used light colors instead of dark colors to help minimize thermal energy transmission, which is a scientifically sound design idea. Also, many teams used aluminum foil as part of their insulated penguin dwelling prototypes, since metals are shiny and reflect radiation. Interestingly, this concept of metals reflecting light was also found in a study that was meant to investigate students' conceptions about conduction (Paik et al., 2007). Presented with several materials, many students in the study chose aluminum foil as the best material to wrap an ice cube in to keep it cold. For some students, their justification was that since metals are shiny and reflect light, they thus also reflect heat (i.e., do not conduct heat). Neither of these studies mentioned anything about transmitting radiation.

2.3.3 A Note About Heat: Language Is Problematic

In addition to being conceptually difficult, the science content area of heat has another layer of difficulty that makes it challenging to teach and learn; that added difficulty is a problem of language. "*Heat* presents one of our most serious linguistic problems" (Romer, 2001, p. 107). The first challenge is that how key terms such as "heat" and "temperature" are used in everyday language is often different from how we use those terms in science language (Bauman, 1992; Wiser & Amin, 2001). For example, when talking about weather, the phrase, "heat versus humidity," is sometimes used when "temperature versus humidity" would be more scientifically correct (Bauman, 1992).

The second challenge is that in many Western languages, including English, much of the way we use "heat" is based on caloric theory; this includes terms such as "heat," "heat flow," "heat capacity," and even "heat transfer" (Harris, 1981; Romer, 2001). Indeed, the second challenge is not as problematic for non-Western languages. In Sotho, for example, there are different terms for "the object is hot" and "the person feels hot" (Hewson & Hamlyn, 1984). This latter term is used as a cultural metaphor in a way that roughly fits the kinetic model. Ten students and 10 adults who were native Sotho speakers but learned school science in English were interviewed. Although their conceptions were generally crude and naïve, 12 participants had pre-kinetic or kinetic conceptions, and only 2 had caloric conceptions. The authors attributed the large ratio of kinetic to caloric conceptions to the fact that the participants likely avoided everyday language problems that Westerners have about heat.

An extension of this second challenge is that even in scientific communities and textbooks, the term “heat” is often used instead of “thermal energy” (Bauman, 1992). In other words, “heat” is used as a noun in terms of the amount of energy that an object has and also as a verb in terms of a process of energy transfer. When performing calculations, experts correctly use work (W) and heat (Q) to mean energy in transit, as opposed to state functions such as internal energy (U); however, they still use common qualitative language about “heat” that implies an idea of heat as a substance than an object can have (Romer, 2001).

Even though experts agree that “heat” is problematic, they disagree about how to fix the problem (Bauman, 1992; Pushkin, 1997; Romer, 2001). For example, Romer (2001) finds the terms “heat flow” and “heat transfer” acceptable, provided that it is emphasized that in these cases, “heat” is an adjective. In contrast, Bauman (1992) proposes that “heat” only be used generically, and “thermal energy transfer” should be used as the scientific, technical term. Pushkin (1997) thinks that “heat” should be used only as a verb or process rather as a noun (i.e., “heat energy”). Because even experts cannot agree about how to fix the linguistic problems that accompany the use of the term “heat,” these linguistic problems make learning thermal energy and heat transfer concepts even more challenging for students.

Another issue with language is less specific to heat transfer. In middle school science, “students often get terms wrong or use them inconsistently” (Lewis & Linn, 1994, p. 666). However, some students, usually more as they get older, pick up scientific-sounding phrases quickly so they seem to have scientific conceptions (Clough & Driver, 1985). Due in part to time limitations, teachers are often not able to probe students’ thinking enough to determine whether they actually have a scientific conception or are just able to say the right words. The language issues described here can make it difficult both for students to learn heat transfer conceptions and for teachers to assess and interpret those students’ conceptions.

2.4 Conceptual Framework: The STEM Integration Framework

As stated previously, there are several definitions and models of STEM integration (Bybee, 2013; NAE & NRC, 2014). Therefore, it is necessary to clearly define one for this study; the model described here was the version used by the larger project within which this study was situated. The STEM Integration Framework describes seven components deemed necessary for high-quality engineering design-based STEM integration in pre-college settings (Moore, Stohlmann, et al., 2014). The STEM Integration Framework uses the *Framework for Quality K-12 Engineering Education* (Moore, Glancy, et al., 2014) as the engineering connection, which itself was based on a synthesis of engineering content and practices describe in state science standards with additional input from disciplinary experts. The *Framework for Quality K-12 Engineering Education* describes nine key indicators necessary for quality pre-college engineering education experiences. However, for the purposes of this study, I only describe the key indicators of the *Framework for Quality K-12 Engineering Education* that are relevant to the seven components of the STEM Integration Framework.

According to the STEM Integration Framework, a high-quality STEM integration experience should include: (1) a realistic context that motivates and engages students; (2) a chance for students to do engineering design practices in order to solve an engineering design challenge; (3) at least one opportunity for students to learn from design failure and redesign; (4) standards-based science and mathematics content and practices that are needed to create a design solution; (5) the use of student-centered pedagogies for classroom instruction including a requirement for students to use evidence-based reasoning to integrate engineering with science and mathematics; (6) opportunities for students to develop teamwork and communication skills; and (7) engineering design throughout the entire unit as a reason for learning the science and mathematics (Moore, Stohlmann, et al., 2014). While the STEM Integration Framework shares certain features and ideals with other models of STEM integration (e.g., Breiner, Harkness, Johnson, & Koehler, 2012; Wang, Moore, Roehrig, & Park, 2011), it serves as the specific framework that guides this study and was fundamental to the larger project in which the study is situated. In the following sections, each component of the framework is described in more detail, with special attention paid to those components most important to the study: (2) solve an engineering design challenge; (3) redesign; (4) standards-based science and mathematics; and (6) teamwork and communication.

2.4.1 Realistic Context that Motivates and Engages Students

Meaningful contexts are important in science education (e.g., Bolte, Streller, & Hofstein, 2013; Hoffman, 2002) and engineering or design-based education (e.g., Carlson & Sullivan, 2004; Guzey, Moore, & Morse, 2016). Contexts need to be realistic and accessible to students so that they can personally connect with it, which encourages their participation in and engagement with the activity (Brophy et al., 2008; Kolodner et al., 2003). In one study of seven different engineering design-based STEM integration curricula, it was found that all teams considered the ease of use of their design ideas, regardless of how much the curricula emphasized the end user or not (Siverling et al., submitted). The authors attributed this student concern about the end user's ability to use a solution to the motivating and engaging contexts that were part of the seven curricula. This study is one example that demonstrates that when the context of a problem is motivating and engaging to students, they are able to personally invest in it.

2.4.2 Use Engineering Design Practices to Solve an Engineering Design Challenge

2.4.2.1 Importance.

As part of their report, the NAE and NRC (2009) recommended three principles for engineering in K-12 education. The first of these principles is to emphasize engineering design. Engineering design is also a key component of practices and disciplinary core ideas in the NGSS (NRC, 2012; NGSS Lead States, 2013). In the standard's science and engineering practices, there are two practices that are specifically for engineering, and both relate to design: defining problems and designing solutions. Similarly, the engineering disciplinary core ideas are also about design practices: defining and delimiting engineering problems, developing possible solutions, and optimizing design solutions. In addition to national reports and standards that state the importance of engineering design practices, many curricula and reports have successfully used engineering design in pre-college settings (e.g., Kolodner et al., 2003; Mehalik et al., 2008; Schnittka & Bell, 2011; see sections 2.1 Design-Based Learning/Science/STEM Integration and 2.2 Design-Based Curricula that Include Heat Transfer Concepts section for more details).

2.4.2.2 Engineering design process.

In order to understand the interactions of science and engineering during an engineering design-based STEM integration unit, it is necessary to define a model of engineering design. There are multiple engineering design process models in pre-college curricula and other sources, and previous research has compared and synthesized them (Guerra, Allen, Crawford, & Farmer, 2012; Moore, Glancy, et al., 2014). This research project is guided by the engineering design process described in *The Framework for Quality K-12 Engineering Education* (Moore, Glancy, et al., 2014). The first indicator of this *Framework*, which is the most important for this research project, is Process of Design (POD).

In the *Framework*'s POD model, there are six steps paired into three sub-indicators: Problem-Background, Plan-Implement, and Test-Evaluate (Moore, Glancy, et al., 2014). The first sub-indicator, Problem-Background, can also be considered the *problem scoping* stage of this model of POD. Students define the Problem, which includes identifying the engineering problem and its criteria and constraints. They then need to learn Background information, which includes concepts and skills, necessary to solve the engineering problem. The second two sub-indicators, Plan-Implement and Test-Evaluate, can be thought of as the *solution generation* stage of POD. In order for students to develop a Plan for a design solution, they must use divergent and convergent thinking: generating multiple possible design ideas and then comparing the strengths and weaknesses of those possibilities to narrow down to one proposed design solution. They then Implement this plan, which can mean building a prototype if the design solution is meant to be a product, or carrying out a procedure if the design solution is a process. Students Test this prototype, model, or process in order to collect data about its performance. They use these data to Evaluate the design solution, determining whether the proposed solution satisfactorily meets the criteria and constraints of the engineering challenge or if they need to redesign. Because engineering design is iterative, these six steps do not need to be followed in this exact linear order; rather, students may go back to another step in POD as needed.

2.4.3 At Least One Opportunity to Learn from Failure and Redesign

Another fundamental component of engineering design processes is their iterative nature, which includes the ability to learn from previous design failures and redesign (Guerra et al., 2012;

Moore, Glancy, et al., 2014). In situations where students are able to do many iterations of their design solutions, students learn from their own and from others' mistakes (Barnett, 2005; Sadler, Coyle, & Schwartz, 2000) and build self-confidence and remain engaged because they experience small successes and failures (Sadler et al., 2000). Students on teams that create and test more designs tend to have more successful final design solutions (Apedoe & Schunn, 2012) and learn more science knowledge (Chao et al., 2017). Even in design-based curricula where the number of iterations are limited to two or three, redesign is still important. In some cases, students are able to use a larger amount of relevant science ideas and language in the second or third design iteration, (Hmelo et al., 2000; Puntambekar & Kolodner, 2005), and the performance of their designs tends to improve with iteration (Schnittka, 2012). In sum, iteration and redesign not only reflect the work of engineers in the profession, but they are also opportunities for pre-college students to learn from failure, improve their design's performance, and learn science content.

2.4.4 Standards-based Science and Mathematics Content and Practices

As recommended by the NAE and NRC (2009), the second principle for pre-college engineering education is to "incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills" (p. 5). A frequent method of determining what is important and developmentally appropriate is to use standards, whether at the state or national level (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010; NGSS Lead States, 2013). The *Framework for Quality K-12 Engineering Education* also supports this idea, with one of the key indicators being Apply Science, Engineering, and Mathematics Knowledge (Moore, Glancy, et al., 2014). There are two main reasons for integrating science and mathematics with engineering at the pre-college level. First, it reflects the practice of engineering, which requires the application of science and mathematics in order to solve engineering problems (Moore, Glancy, et al., 2014). Second, by having students make connections between the STEM disciplines, which includes the connection of applying science and mathematics to engineering, it is thought that students can learn more and think more deeply about each individual discipline (NAE & NRC, 2014). (See sections 2.1 Design-Based Learning/Science/STEM Integration and 2.2 Design-Based Curricula that Include Heat Transfer Concepts sections for more details on how engineering design has contributed to student learning of developmentally-appropriate science content and practices.)

2.4.5 Student-Centered Pedagogies for Classroom Instruction and Use Evidence-Based Reasoning to Integrate STEM

Another important component of education, but especially pre-college engineering and STEM integration, is the use of student-centered pedagogies during instruction (Furner & Kumar, 2007; Smith, Sheppard, Johnson, & Johnson, 2005). In one study, student-centered pedagogies such as small group work and requiring students to create their own storyboards with key science concepts resulted in students achieving higher science content knowledge gains during a design-based unit (Schnittka, 2012). This is one example that demonstrates the benefit of using student-centered pedagogies and allowing students to explore and learn themselves.

An especially important type of student-centered pedagogy is to have students use evidence-based reasoning, which is the practice of justifying design ideas and decisions (Siverling, Suazo-Flores, Mathis, Guzey, & Moore, submitted). Evidence-based reasoning is a type of *engaging in argument from evidence*, one of the key practices in the NGSS (NRC, 2012; NGSS Lead States, 2013). When students use evidence-based reasoning, they can integrate the disciplines of STEM by supporting their engineering design ideas and decisions with reasoning related to science, mathematics, and the engineering problem (Mathis et al., 2018; Siverling, Suazo-Flores, Mathis, & Moore, submitted).

2.4.6 Develop Teamwork and Communication Skills

Teamwork and communication are important components of engineering practice and are thus frequently recommended in pre-college settings. In the NAE and NRC report, *Engineering in K-12 Education* (2009), collaboration and communication are listed as two engineering habits of mind that are also important skills for students to develop as 21st century citizens. For collaboration, it is essential that students learn to listen to and use the background knowledge and perspectives of their team members. Communication is not only necessary for collaboration, but it is also important for students to learn how to communicate with stakeholders outside of the team, for example learning about stakeholder needs and justifying their design solutions to stakeholders. Teamwork and communication are also two of the nine indicators in the *Framework for Quality K-12 Engineering Education* (Moore, Glancy, et al., 2014). These descriptions are similar to those in the NAE and NRC report. By doing engineering design in a team, students can learn to contribute to a project as a member of a team, and they can learn interpersonal skills related to teamwork. Learning to communicate like engineers is also helpful to students, since engineers communicate in a variety of ways. Engineers need to be able to describe and explain ideas in technical and everyday language, and they need to represent these ideas in different ways (e.g., images, three-dimensional prototypes, equations, charts and tables).

Teamwork and communication are not just important skills for students to develop that reflect skills of engineers in the profession, but they can also help students learn STEM content and practices through engineering design-based STEM integration curricula. Collaborative and cooperative learning have long been important pedagogies in pre-college education (Johnson & Johnson, 1994; Johnson, Maruyama, Johnson, Nelson, & Skon, 1981; Kagan, 1992). These pedagogies are built on foundations of learning theories related to social constructivism (Kolodner et al., 2003; Vygotsky, 1986). By working in teams, students are able to "build knowledge synergistically" (Riskowski et al., 2009, p. 192), which can include working through their alternative conceptions with peers and correcting them (Mathis et al., 2018). Student teams can also learn from other teams in a classroom, whether that is getting ideas for design features from other groups' designs (Hmelo et al., 2000) or refining their design ideas and justifications by presenting them to and answering questions from the rest of the class (Puntambekar & Kolodner, 2005). These discussions within and between small groups can be even more effective for student learning and design prototype performance when they have some guidance by the instructor (Guzey & Aranda, 2017; Puntambekar & Kolodner, 2005).

In addition to communicating as they collaborate in teams, students can also learn through communication by writing in engineering notebooks and by communicating (e.g., presenting, writing a letter) their final design to the client. Students who write more or use more time taking notes in engineering notebooks tend to learn more science knowledge (Chao et al., 2017; Wendell & Lee, 2010). In some cases, engineering notebooks and portfolios can show student learning in a way that pre-post assessments cannot; this is especially important for students who struggle with reading and writing (Doppelt et al., 2008). End-of-unit communications seem to be particularly important. Reflecting on actions and reasoning that led to final design decisions (Wendell & Lee, 2010) and writing recommendations to the client about final design solutions (Gale et al., 2018) provide students opportunities to solidify their science learning. Team presentations about their design solutions to the rest of the class can also be important for student learning, since students have to think more deeply about science concepts in order to justify their design solutions and answer questions about the solutions from their teacher and peers (Hmelo et al., 2000; Puntambekar & Kolodner, 2005). As shown by the examples given above, teamwork and communication are important for student learning of content in addition to being important engineering skills.

2.4.7 Engineering Design Throughout the Unit

A final component of high quality engineering design-based STEM integration curricula is that engineering design is present throughout a curricular unit. In other words, the curricula are organized so that each lesson is related to the engineering challenge, starting with introducing the engineering problem, then exploring the science and mathematics needed to solve the engineering problem, and finally designing (and redesigning) solutions to the problem (Guzey, Moore, & Harwell, 2016). This logical and sequential order of lessons contributes to the overall quality of the design-based units. Students who participate in engineering design-based STEM integration curricula that are organized in this integrated way perform significantly better on assessments of engineering learning than students who participate in curricula where engineering is the culminating project, treated as an "add-on" to the end of several science and mathematics lessons (Crotty et al., 2017).

CHAPTER 3. METHODS

This section describes the research design and methods used to answer this study's research questions:

- During an engineering design-based STEM integration unit:
  - What scientific and alternative conceptions about heat transfer does a team of middle school students use?
  - How do engineering design, redesign, teamwork, and communication influence students' use of these conceptions?

This section includes detailed explanations of: the research design; information about the context, including the broader project, setting and participants, and curricular unit description; data collection methods and analysis; and other considerations such as validity and reliability, the role of the researcher, and limitations of the study.

3.1 Research Design

In this study, I used case study as the research design. Case study research is useful when "a how or why question is being asked about a contemporary set of events, over which the investigator has little to no control" (Yin, 2018, p. 13). In this research, I explored what scientific and alternative conceptions about heat transfer students used throughout an engineering design-based STEM integration unit in order to determine how different features of engineering (i.e., engineering design, redesign, teamwork, and communication) influenced their use of these conceptions. In this case, the event that the participants experienced was a particular engineering design-based STEM integration curricular unit in a middle school classroom. Because the teacher was in charge of the classroom, I had little control over how the classroom functioned. Additionally, while student participants' actions and conversations were guided by the teacher, what the student team chose to specifically do and discuss was mostly up to them. Because of these circumstances, I chose the case study design for this research.

Additional features of case study research align with the goals of this research. First, an important feature of case study research is that the case is bounded (Creswell, 2013; Yin, 2018). For this study, the case was bounded by space and time since I followed one team within one teacher's seventh-grade science class for the duration of the engineering design-based STEM integration unit. Second, case studies require in-depth investigation of a system or systems in order to understand their complexities (Stake, 1995). I was able to explore the student team's conceptions in a detailed manner because of the number and variety of data collection methods I used, which included classroom observations and field notes, video recordings, audio recordings, and student artifacts. More information about classroom context, curricular unit, student teams, and data collection methods are addressed in later sections of this chapter.

The specific research design within case study that was used for this study was an embedded, single-case design. In this study, the single case was an example of struggling case, in contrast to an exemplary case. In education research, it is important to not only investigate typical students or students who do well, but also those who experience difficulty with the educational interventions. By focusing on a team that struggled with the intervention, we can better understand more challenging aspects of an intervention. This study is also an embedded case study design, which occurs when certain elements of the case are also important sub-units of study (Yin, 2018). In this study, the embedded units are individual students within the team that is the case. As is typical in embedded case studies, the communications of each student, or subunit, were analyzed throughout the unit, and the data were also analyzed at the case level. During the case description in chapter 4, the results are presented as the story of the student team because the curricular unit was a team-based unit. However, when the individual students' stories are important to describe based on what happened during the unit, those parts are presented individually. Additionally, one student's results are highlighted due to the unique nature of her participation, or lack thereof, in the unit.

Finally, this study is considered a descriptive case study, rather than an exploratory or explanatory case study (Yin, 2014). According to Yin (2014), case studies are considered descriptive when their "purpose is to describe a phenomenon (the "case") in its real-world context" (p. 238). This is different from exploratory and explanatory case studies, since their purposes are to generate research questions for a subsequent study and to explain why or how a condition that exists within the case came to be, respectively (Yin, 2014). In this study, the phenomenon being described is the students' use of conceptions about heat transfer throughout an engineering design-based STEM integration unit.

3.2 The EngrTEAMS Project

This study is set within the context of a larger, funded five-year curriculum and teacher professional development project, Engineering to Transform the Education of Analysis, Measurement, and Science (EngrTEAMS) in a Team-Based Targeted Mathematics-Science Partnership. The project was guided by a design-based research (DBR) research design (The Design-Based Research Collective, 2003). In DBR, education innovations, theory, and practice are deeply intertwined (The Design-Based Research Collective, 2003). Innovations are based upon theories of learning, and the results from using these innovations in practical contexts should inform these theories. An important feature of DBR is that "development and research take[s] place through continuous cycles of design, enactment, analysis, and redesign" (The Design-Based Research Collective, 2003, p. 5). This iterative nature of DBR was a key component to achieving the goals of the EngrTEAMS project. The overall goal of the project was to improve STEM integration education in fourth through eighth grade classrooms, and it did so through two primary means: curriculum development, and teacher professional and leadership development.

The first aim of EngrTEAMS was to develop high quality, engineering design-based STEM integration curricular units for upper elementary and middle school classrooms. As stated previously, these units were created with guidance from the STEM integration framework (Moore, Stohlmann, et al., 2014). With mentoring and coaching support from the EngrTEAMS project team, the initial versions of the curricular units were developed and implemented by teams of teachers who attended the EngrTEAMS teacher professional development (PD) institutes. Guided by the DBR research design, these units were then improved through an iterative process of research, modification, and implementation. The engineering design-based STEM integration unit that was used for this study was in its fourth iteration.

The second aim of the project was to support teachers in understanding and practicing reform-based science instruction; this was done through PD. Note that the following describes the PD institute for the fourth iteration of curricular units; PD experiences for prior iterations are not explained here because they are irrelevant for this study. During the summer prior to the implementation of the engineering design-based STEM integration unit used in this study, teachers participated in a one-week PD experience about the unit. While this PD included general information about content and pedagogies related to engineering design and STEM integration, the main focus of the PD was the unit itself. The teachers in the PD experienced a modified version of each lesson in the unit, both participating in the activities to gain a student perspective and also thinking about each lesson from a teaching perspective. As part of the PD, all teachers were provided with a kit of materials for the unit's implementation and also agreed to partake in the fidelity of implementation study as part of the larger EngrTEAMS project (i.e., implement the engineering design-based STEM integration unit with at least one class period of students, allow researchers to be in their classrooms for data collection).

3.3 Setting and Participants

3.3.1 School and District

The data for this study were collected from a classroom in a junior/senior high school in a rural school district in the Midwest. At the time of this study, this school served around 900 7^{th}-12^{th} grade students, with 10% students of color and 43% free/reduced price lunch eligible. The school district is in a Midwestern state that has not adopted the mathematics (CCSSM) or science (NGSS) standards put forward for state adoption in the US. However, the state recently revised their state mathematics and science standards to more closely align with the the CCSSM and NGSS standards. For example, the new state science standards have eight scientific and engineering practices that are very similar to the eight practices in NGSS. Therefore, there is an expectation that engineering will be included in pre-college education. For this district's elementary and junior high schools, it is the responsibility of science teachers to include engineering in their classrooms.

3.3.2 Teacher

Mr. Parker (pseudonym), the teacher whose classroom was the specific setting for this study, taught three sections of seventh-grade science and three sections of high school earth science. At the time of data collection, he was in his sixth year of teaching; all of his teaching experience had been in science and with junior and senior high school students. Mr. Parker had limited previous experience with implementing engineering design and STEM integration activities in his classroom, namely a few one-day laboratory activities where students had to solve a problem based on their understanding of science concepts. This was Mr. Parker's first year implementing engineering design-based STEM integration using the model of the EngrTEAMS project.

Mr. Parker was selected for this study using criterion sampling (Miles & Huberman, 1994). The EngrTEAMS PD had teachers from multiple locations within the Midwestern part of the United States. Two of these teachers were accessible to the researcher without extended travel, and each taught at least three class periods in which they would implement the engineering design-based STEM integration unit. Therefore, these teachers were considered as possible research participants for this study. I approached these two teachers about the possibility of conducting this dissertation study within their classrooms, and Mr. Parker volunteered for the study.

3.3.3 Students

3.3.3.1 Criteria for selection.

One student team from the first of Mr. Parker's three seventh-grade class periods was chosen to be the case for this study using the purposeful sampling technique of criterion sampling (Miles & Huberman, 1994). For this type of sampling, cases are chosen based on specific criteria desired for the study. In this research project, the first criterion for selection was that all students in the team consented to the study, which all of these students did. The second criterion for selection was to have a more communicative team in the classroom. While other data types were collected, the two that were most useful in data analysis were audio/video recordings of the student team and the individual and team written artifacts. Therefore, it was necessary that the student team contained members who would provide sufficient oral and written data to answer the research questions. I determined which student team best met this criterion by asking the teacher for his recommendation, as he was the expert about his students as individuals and as team members. Also, prior to the implementation of the unit, I visited Mr. Parker's classroom for several days to have conversations with the students and develop a rapport with them so that they felt comfortable openly communicating when I was around. In this way, I aimed to ensure that a highly communicative student team was chosen for the study. To clarify, prior student achievement level was a not a criterion of student and team selection, and I explicitly told this to Mr. Parker when he recommended teams for the study. The important feature of the team members was that they were willing to communicate in spoken and written formats, not that they demonstrated a certain level of achievement in general or science specifically. During the implementation of the unit, it became clear that the student team had difficulty applying science concepts to designing a solution, especially when compared to other teams in the class. Therefore, although I did not initially seek out a struggling team, that aspect ended up being an important part of the case.

3.3.3.2 Student team.

The student team that is the focus of this study was made up of four students: Dylan, Marie, Noelle, and Sheldon. The names of the students are all pseudonyms chosen by the students themselves. Their team name was Swedish Fish; this name, as well as the other team names in the class, has not been changed. In terms of demographic information about the students, the school shared a limited amount of information about gender, race, and which elementary school (grades K-6) the students had attended before coming to the junior/senior high school (grades 7-12). The information about gender and race are summarized in Table 3.1. The school did not provide any information about whether the students qualified for free or reduced price lunch, had special needs, or were English language learners. I also was not given access to information about their past academic achievement, in general or specifically in science courses.

Table 3.1. *Demographic information about the student team members*

Student	Gender	Race
Dylan	Female	White
Marie	Female	Not white
Noelle	Female	White
Sheldon	Male	White

In order to find out more about the students’ backgrounds, I asked them questions about their previous experiences with engineering and with heat transfer-related activities such as cooking during the implementation of the unit.

All of the students had done an engineering activity during the previous school year. Dylan, Marie, and Noelle had attended the same elementary school in the district, so they had all done a Rube Goldberg project during a science unit about simple machines. The had to use their knowledge of simple machines to create a device that completed a simple through a more difficult series of steps. For example, Marie’s team’s device needed to staple a piece of paper, and Noelle’s team’s device had to open a book. Dylan did not provide any further information about her team’s project other than to describe that her group was drama-filled. Sheldon had attended a different elementary school in the district, and that school’s sixth-grade engineering project was to build bridges first out of toothpicks and marshmallows and then out of popsicle sticks. They also tested the bridges by hanging increasing amounts of weight from them until they broke. Although they were slightly different engineering activities, all four students had at least one engineering experience through their formal schooling.

In addition, several of the students on the team discussed doing engineering-type activities at home. Sheldon, Noelle, and Marie said that they played with Legos, and Sheldon spoke extensively about his experience with Legos. Sheldon and Marie also talked about building items out of wood. Sheldon said that he used old wood and screws at his grandparent’s house to build things. Marie described how she and her father build furniture together; they had built a shelf out of a wooden pallet were currently working on a mirror stand. Noelle said that her brother was an undergraduate student majoring in engineering. At various points during the unit, Marie, Noelle, and Sheldon all explicitly expressed excitement about doing an engineering project. In contrast, Dylan did not contribute much when the team talked about other engineering activities, and when asked if she had done anything similar outside of school, she said she did not.

The student team also had varying prior experience with cooking and baking, activities that can generate many sensory experiences and conceptions about heat transfer. Marie had the most experience since she had to cook every night, and she talked about various items that she cooked and baked. Noelle also spoke about baking cookies and cooking, though she clarified that she mostly made easy things. Sheldon specifically said that he made mac and cheese, and that was it. Based on what items they described cooking, those three students had experiences cooking using the stove and boiling water. When asked about her experience cooking, Dylan initially said that she did not cook or bake at all but later clarified that she did not do it often. However, during the unit, Dylan wrote and spoke about overcooking and needing to reach specific temperatures, which indicates that she at least had some familiarity with cooking and baking. Another indication that the team had firsthand experience cooking and baking was that during the unit, they talked and/or wrote about needing handles on their cooker container so that they would not burn their fingers.

Students drew on these everyday experiences with heat transfer, as well as their previous engineering experiences, while participating in the unit.

3.4 Curricular Unit

3.4.1 Description of Unit

Ecuadorian Fishermen, the engineering design-based STEM integration curricular unit used for this research, was designed to address content and practices related to middle school level physical science, mathematics related to data analysis, and engineering design (Berg et al., 2017). Specifically, the science content addressed in the unit is about temperature, thermal energy, and three methods of heat transfer (i.e., conduction, convection, radiation). These concepts are based on performance indicators at the middle school level in the *Next Generation Science Standards* (NGSS Lead States, 2013). The mathematics focus is creating and interpreting line graphs, which is based on the Common Core State Standards – Mathematics (CCSSM; National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010).

The order of the lessons in *Ecuadorian Fishermen* follows the process of design (POD) described in the *Framework for Quality K-12 Engineering Education* (Moore, Glancy, et al., 2014), with a few changes in terms. All changes in terminology have emerged from results of the design-based research (DBR) process; through iterative cycles of modification, implementation, and research of the EngrTEAMS curricular units, specific engineering vocabulary have changed to be better understood by fourth-eighth grade teachers and students. First, while this model is called process of design (POD) in the *Framework*, the model is called an engineering design process (EDP) in the curricular unit. Second, several of the steps have changed. As described earlier, this POD model is made up of six steps: Problem, Background, Plan, Implement, Test, and Evaluate. In the EDP model in *Ecuadorian Fishermen*, most of these six steps have been renamed: Define (the problem), Learn (about the problem), Plan (a solution), Try (the plan of the solution), Test (the solution) and Decide (about whether the solution is successful). Both of these models are iterative, and both can also be thought of as two overall stages: problem scoping (i.e., the first two steps) and solution generation (i.e., the last four steps).

The *Ecuadorian Fishermen* unit has 12 lessons that are supposed to take approximately three weeks of classroom instruction, assuming one 50-minute class period per day. They follow the POD/EDP model described earlier, including one lesson explicitly requiring redesign and another in which students communicate their final design solution back to the client. Each lesson is described in more detail in Table 3.2. Terminology from both the POD and EDP models are included to show how the lessons map to a design process.

As with other EngrTEAMS project curricular units, *Ecuadorian Fishermen* was designed with guidance from the STEM Integration Framework, which was described earlier (Moore, Stohlmann, et al., 2014). The purpose of using this framework is to ensure the integration of engineering, science, and mathematics, so that students learn science and mathematics concepts and practices and are then able to apply those knowledge and skills to the engineering challenge. Table 3.3 addresses how each of the seven components of the STEM Integration Framework are present in the unit.

Table 3.2. *Ecuadorian Fishermen lesson descriptions, mapped to the Process of Design (POD) and Engineering Design Process (EDP)*

EDP, POD	Lesson	Description
Define, Problem	1: Defining the Engineering Problem	Students receive a letter from their client, The Pescadores Foundation, that describes the engineering problem. They ask the client questions to learn more specific information about the engineering challenge, which is to construct a cheap cooker container for Ecuadorian fishermen so that they can quickly cook fish at the fish market. Students define the engineering problem, including the client, end users, criteria, constraints, and why the problem is important to solve. At the end of the lesson, they identify what they need to learn about in order to design a solution.
Learn, Background	2: Temperature and Heat Transfer & Convection	Students define and learn about the differences between temperature, thermal energy, and heat. They explore the relationship between temperature and the movement of particles in solids, liquids, and gases. They learn that thermal energy is transferred from regions of higher temperature to lower temperature. Finally, they observe a demonstration to learn about heat transfer through convection.
	3: Heat Transfer Through Conduction	Students learn about heat transfer through conduction by completing an ice cube experiment. They place ice cubes on top of different materials and observe which ice cubes melt more quickly. Students categorize these materials as conductors or insulators.
	4: Heat Transfer Through Radiation	Students learn about heat transfer through radiation and also that materials can absorb, reflect, or transmit light. They perform an experiment in which they collect temperature data of air inside cups that have lids made of different materials. These cups are placed under heat lamps, and students measure the change in temperature over time.
	5: Analyzing the Absorption Property of Materials	Students use graphs to interpret the data they collected during the radiation lab. They create a temperature vs. time graph and analyze it to determine that the rate of temperature increase slows down over time. Also, students qualitatively analyze a graph with multiple lines to determine which materials had higher temperature changes and which had lower. They relate these data to the materials properties of absorption, reflection, and transmission.
	6: Getting to Know the Context	Students are introduced to and make observations about the agar fish and the solar oven. Based on the solar oven's structure and materials, students describe how each of the three types of heat transfer are present in the solar oven and predict how that might affect their design solution.

Table 3.2 continued

Plan	7: Exploring Materials and Planning: Idea Generation	First, students make observations about the materials available for the engineering design challenge and predict which ones will be conductors vs. insulators, and which will absorb, transmit, and reflect radiation. Then, students individually generate at least three ideas for their first cooker container prototype. They use a list of materials with their costs, as well as what they have learned about heat transfer, to generate multiple designs.
	8: Planning: Idea Selection and Evidence-Based Reasoning	In their design teams, students share their individual design ideas. The team decides on one idea for a design solution, which may be one of the ideas or combinations of several ideas. Also, the student team uses evidence-based reasoning to justify each part of the design.
Try, Implement	9: Trying, Building the First Prototype	The student teams each implement their planned design solution by constructing a prototype cooker container.
Test & Decide, Evaluate	10: Testing and Deciding About the First Prototype	To test their prototype cooker containers, student teams place their prototypes, each of which contains an agar fish, in the classroom solar oven for 10 minutes. They measure the initial and final temperature of the fish and then calculate the temperature change. After student teams share their design plan, prototype features, and results with the whole class, the entire class compares the results to determine which features seemed to make designs most successful. The student design teams then decide how well their prototypes met the criteria and constraints.
Redesign: all steps, especially Solution Generation	11: Redesigning a Second Prototype	Based on the analysis and discussion about the initial design results, student teams work to improve their cooker container prototypes. They develop a new design and either construct an entirely new prototype or make adjustments to their first prototype. They then retest and reevaluate the second design. Students compare and contrast their second design's results with those of the initial design in order to decide which design to recommend to the client as the better solution.
Communicate	12: Communicating with the Client	Student teams create a poster or letter for their client, the members of the Pescadores Foundation. The describe their design with text and drawings, and they provide evidence and justify how their design is a valid solution to the engineering challenge.

Note: These lesson descriptions match or are slightly adjusted versions of the lesson descriptions in the *Ecuadorian Fishermen* document. Adapted from *Ecuadorian Fishermen: An EngrTEAMS Unit* (pp. 10-11), by K. Berg et al., 2017, West Lafayette, IN: School of Engineering Education, Purdue University. Copyright 2017 by the Purdue Research Foundation. Adapted with permission.

Table 3.3. *Mapping the seven STEM Integration Framework components to Ecuadorian Fishermen curricular unit*

Component of STEM Integration Framework	How component is addressed in *Ecuadorian Fishermen* curricular unit
1. Realistic Context that Motivates and Engages Students	Fishermen from Ecuador have mastered the ability to catch the best fish in the area, but now they are interested in selling cooked fish at the fish market in addition to the raw fish they already sell. By selling cooked fish, the fishermen predict that they will be able to earn more money at the fish market, which will improve the quality of life for themselves, their families, and their villages.
2. Use Engineering Design Practices to Solve an Engineering Design Challenge	The Ecuadorian Fishermen have access to large solar ovens which will allow them to cook the fish using energy from the sun and from warm coals underneath the solar ovens. However, they need small cooker containers to hold the fish while they are cooking in the solar oven. Students are tasked with designing these cooker containers, which for the purposes of this engineering challenge need to cook an agar fish by increasing its temperature as much as possible in the 10 minutes it is in the solar oven, while also minimizing cost. While the general idea of the solar oven and cooker containers is realistic, the specifics of both have been modified to work in a middle school classroom setting.
3. At Least One Opportunity to Learn from Failure and Redesign	All student teams must redesign at least once, completing all solution generation steps a second time: creating a new plan, implementing a second prototype, testing the second prototype, and evaluating the second prototype's performance. Additional redesign cycles may be done if time allows.
4. Standards-Based Science and Mathematics Content and Practices	The unit partially or fully addresses middle school NGSS science standards related to temperature, particle motion, thermal energy, heat transfer, kinetic energy, and waves: MS-PS1-4, MS-PS3-3, MS-PS3-4, MS-PS3-5, and MS-PS4-2. NGSS also includes engineering design performance expectations, which are also in this unit: MS-ETS1-1, MS-ETS1-2, MS-ETS1-3, and MS-ETS1-4. CCSSM related to the mathematics concept and practice of data analysis, especially making and interpreting graphs that are relevant to this unit are: 5.G.A.1, 6.EE.C.9, and 8.F.B.5.
5a. Student-Centered Pedagogies for Classroom Instruction	As much as possible, activities within each lesson are student-centered. This includes hands-on experiments students carry out during the science-focused lessons, as well as student teams designing unique solutions during engineering solution generation lessons.

Table 3.3 continued

5b. Use Evidence-Based Reasoning to Integrate STEM	Students have to not only record their design ideas and solutions, but also justify them with evidence, at least four times during the unit. Once a student team has decided upon their initial design plan, they fill out an EBR graphic organizer. This graphic organizer includes sections for students to describe: the problem (including criteria and constraints), simplifying assumptions, their design idea, supporting evidence, and justification. The student teams also use EBR while evaluating their first design and planning their second design, though these notebook prompts are shorter versions of the original EBR graphic organizer. While student teams create their communication (e.g., letter, poster, presentation) for the client, they are prompted to include all information from the EBR graphic organizer sections.
6. Develop Teamwork and Communication Skills	Students keep an engineering notebook throughout the unit. They record answers to questions and prompts about their science, mathematics, and engineering knowledge and ideas. Students orally communicate with others in their design team, as well as the whole class, for at least part of every lesson in the unit. The few times that students work individually are almost always preparation for a team activity or discussion. For example, several of the engineering notebook prompts include sections for “My response” and “Team response”; this allows students to think about the question or prompt individually first and then later record the team consensus. In addition to communicating within their team and among teams, students also communicate with their client, asking questions when defining the problem and creating a final communication relaying their design to the client.
7. Engineering Design Throughout the Unit	The five-minute classroom introduction to each lesson after the first lesson is a review of engineering design, including the engineering design challenge and what step of the process of design the students are on. This allows students to connect the activities and learning of that day to the overall goal of the unit, which is to solve the engineering design challenge.

3.4.2 Implementation of Unit

Mr. Parker implemented the *Ecuadorian Fishermen* unit during all three of his seventh-grade science sections. The team observed in this study was in his first seventh-grade science class of the day. This class had 22 students at the beginning of the unit's implementation, 16 girls and 6 boys. During the unit, a new female student joined the class; she was placed on a team that was not the student team that was the focus of this study, and therefore her addition mid-unit does not affect this study.

Mr. Parker's implementation of the *Ecuadorian Fishermen* unit took 21 class periods, 18 days before winter break and three after. Most class periods were 40 minutes long. However, others ranged in length from 25 minutes to 50 minutes due to a several factors: different schedules on Fridays, different schedules on the days immediately prior to winter break, and different schedules after break because of a number of 2-hour late starts due to weather.

3.5 Methods of Data Collection

In order to achieve the in-depth description and understanding that case study research requires, I collected multiple sources of data (Creswell, 2013; Yin, 2018). During the 21 days of unit implementation, I was present for every class period to observe and take field notes. Each day's classes were also video-recorded using two cameras. The first video camera was placed near the student team. When the student team was working in a small group, the video camera was focused on them and whatever they were working on. In this set-up, the camera was placed near the edge of the table the team shared, which meant that it was closer to Marie and Noelle, with Sheldon and Dylan further away. Other times (e.g., teacher lecture, whole class discussions), the video camera was moved to be on the table shared by Noelle and Dylan, with Marie and Sheldon at the table behind them. The second video camera was set up to view the whole classroom; Mr. Parker wore a microphone with the audio feed connected to this camera. I recorded a third source of audio on the iPad Pro that I used to digitally record field notes. I carried this data source around the classroom as I took notes.

I also collected student artifacts from the unit, including pictures of the teams' prototypes and copies of their sketches and written work in the engineering notebooks. To capture the progressions of students' use of heat transfer through an engineering design-based STEM integration unit, I took pictures of their notebooks at the end of each day so I could distinguish what information they recorded in that class period.

Although I did not assist with instruction of the *Ecuadorian Fishermen* unit, I acted somewhat as a participant observer. Throughout the unit, I occasionally asked the students in the focus team to further explain themselves when they talked about heat transfer concepts. For example, I asked, "What do you mean by that?", a few times when they said or wrote something that was unclear. The purpose of this was not to guide the students through the unit or lead or change their conceptions, but rather to have them more thoroughly verbalize their conceptions about heat transfer so that they were captured in the data. When the students in the student team asked me questions, I tried not to answer them unless they required relatively straightforward answers unrelated to the unit (e.g., "What time do we get out of class today?") On a few occasions, I acted more like an aide in the classroom, asking the student team a prompting question or helping a student think through a difficult concept. For example, there were a few times when the student team fell silent during small group work time, so I asked a question in an attempt to start a new team discussion. However, I tried to limit these kinds of interactions, since I was attempting to collect data in as much of a naturalistic classroom setting as possible. Although I tried to not act as an aide to the student team, my presence near the student team potentially affected Mr. Parker's interactions with the student team. Even though much class time was spent on small group activities, and Mr. Parker used this time to interact with the student groups, he tended to interact less with the student team that is the focus of this study than the other five teams in the class.

3.6 Ethics of Data Collection

Institutional Review Board (IRB) approval was obtained for this study. For purposes of ethical research, I supplied assent and consent forms to all students in the class and their legal guardians, respectively. One student in the class did not consent to the study; this student was therefore not included in the data collection, and I angled the whole class video camera so that the student was not in frame. All four students in the team assented and their legal guardians consented to them being in the study. I also supplied Mr. Parker with a consent form, since I observed and video-recording his classroom. The school district also approved of this research through a letter of support submitted to the IRB. To ensure the participants' confidentiality, the data were secured on a password protected server that has been approved within the IRB protocol. Also, all names in the study, excluding the team names chose by students in the class, are pseudonyms.

3.7 Data Analysis

Case study research does not require the use of a specific analytic strategy (Yin, 2018). For this study, I used a data analysis strategy that combined procedures from qualitative content analysis (QCA), memoing, and elements of case study analysis. QCA is a descriptive qualitative approach (Krippendorff, 2013; Schreier, 2012). It is similar to quantitative content analysis in that it is a way to uncover the meaning of texts and other messages through systematic analysis of the material (Neuendorf, 2002; Schreier, 2012). QCA is most useful for material with latent meanings that involve some interpretation, and to which context is important (Schreier, 2012), both of which are true for the data that were collected for this study. A final note about QCA is that it uses both inductive (i.e., data-driven) and deductive (i.e., concept-driven) coding, which was necessary for this study (Schreier, 2012).

3.7.1 Identifying Relevant Data

One of the first steps in QCA is to identify relevant data (Schreier, 2012). Therefore, the first task I did was to listen to, watch, and read through all of the data to identify the parts relevant to the research questions. For this study, data were considered relevant if they involved information about students' conceptions related to heat transfer. This included instances in which relevant vocabulary was used, but also instances where students discussed or wrote about the concepts without using the scientific vocabulary.

3.7.2 Creating Transcripts

Once I identified relevant instances within the data, I created transcripts for each day of implementation. When I transcribed, I primarily used the video data from the camera that was placed near the student team. I also used the video and audio data from the whole classroom camera, as well as the audio from the iPad Pro that I took field notes on, as secondary sources for transcribing. I used these sources to clarify video and audio segments that were unclear on the student team camera. In addition to transcribing the relevant instances about heat transfer, I also transcribed portions before and after the instances when those portions provided additional context for the instances. When I transcribed, I did not include most spoken utterances of "um" and "like" when their removal did not change the meaning of the statement. For example, during the unit, a student said, "What different, like, types of objects, like, make the solar oven, like, heat up faster?" In the transcript, this question was recorded as, ""What different types of objects make the solar oven heat up faster?" I transcribed "um" when it indicated a pause and "like" when it was helpful to understand the full meaning of the statement.

In addition to transcribing the audio of the student team, Mr. Parker, and myself (i.e., the researcher), I also included descriptions of actions such as gestures that the students did that were relevant. These action descriptions were especially useful in clarifying which materials students were talking about. The student team often referred to materials as "this," "that," or "it," but I was able to determine which specific materials they were speaking about by looking at the materials they were holding or pointing to at the time. Although the original transcripts contained all of these actions, several of the gestures were removed when segments of discourse were written in the results in chapters 4 and 5. I added text in brackets, rather than a gesture, to clarify what material or object a student was referring to in those cases where students used terms such as "things" or "that." However, bracketed words and phrases were added only when the context and gestures made it clear that the students were referring to specific words or objects.

For each day's transcript, I included three other pieces of information beyond excerpts of student audio and gestures. First, I made notes summarizing the portions of audio that were not transcribed; these notes included approximate lengths of time the portions lasted. Although these summaries did not directly contribute to answering the research questions, they were useful to understand the story of the case. Second, I included the text and images from each student's notebook that they had written or drawn during that day's class. In other words, each day's transcript included not only what the students said but also their notebook entries. Third, I added any information from the field notes about what happened in the class, when that information was not already evident in the transcribed audio, actions, or notebook entries.

There is one other important note about the daily transcripts, including the transcribed audio and notebook entries. Incorrect grammar was not changed, even when grammar problems made statements more difficult to read. Because I was attempting to interpret students' conceptions about heat transfer from their spoken and written language, I tried to keep the language in the transcripts as true to their original language as possible. However, I did correct misspelled words in their notebook entries to assist with reading because spelling did not change the meanings of words or phrases. As seventh-grade students, they sometimes misspelled words, including key vocabulary terms related to heat transfer. For example, the two most commonly misspelled words were that Marie and Noelle often wrote “tempature” instead of “temperature,” and Marie often wrote “transphers” instead of “transfers.” By changing incorrect spelling but not incorrect grammar, I attempted to preserve the students’ use of language and thus meaning.

3.7.3. Memoing

After I created each daily transcript, I used the process of memoing to document my initial thoughts and reflections about that transcript (Creswell, 2013). Memos are “short phrases, ideas, or key concepts that occur to the reader” (Creswell, 2013, p. 183) that assist researchers in the initial process of exploring data. Each memo was about a specific instance or portion of data, and they ranged in length from one word to several sentences. For example, I wrote, “TG [target group] discusses fully taping the lid down so ‘heat won’t escape’ (only one heat comment in discussion)” for a memo about a student team discussion that occurred when students were building their first prototype. Because they allow researchers to both reflect broadly and form specific, initial ideas about codes and categories, memos are an essential “sense-making tool” (Miles & Huberman, 1994, p. 72). The initial analysis I did with memoing then informed next step of data analysis.

3.7.4 Building a Coding Frame

Another step in the QCA method was to build a coding frame (Schreier, 2012), which I did both deductively and inductively. The first set of categories and sub-categories of the coding frame were deductive and based on three sources, the STEM Integration Framework (Moore, Stohlmann, et al., 2014), the *Ecuadorian Fishermen* curricular documents, and the transcripts themselves. These categories included:

- The student who spoke or wrote the instance (i.e., Dylan, Marie, Noelle, or Sheldon);
- When the instance occurred:
    - In the unit (i.e., day, lesson, and activity within lesson);
    - In what step of engineering POD/EDP; and

- In what general classroom context the instance occurred (i.e., speaking in a small group discussion, speaking in a whole class discussion, writing in an engineering notebook).

This set of categories and subcategories established the context, both in general and specifically in terms of engineering, of each instance.

The second set of categories and sub-categories of the coding frame were about the heat transfer conceptions and how the students used them during the unit. These categories included:

- The heat transfer conceptions spoken or written by the students;
- Whether a conception was a scientific (i.e., correct) or alternative conception; and
- Whether a conception was applied correctly to the design challenge or not.

This second set of categories was created deductively and inductively. Some heat transfer conceptions were based on how heat transfer concepts were presented in the *Ecuadorian Fishermen* unit, and most of the concepts in the unit were themselves based on NGSS (NGSS Lead States, 2013) to ensure that the concepts were developmentally appropriate for middle school students. Other conceptions arose inductively from what the students said or wrote. For the most part, the phrasing of scientific conceptions came from the curricular documents, and the phrasing of alternative conceptions emerged during the memoing process. In some cases, the phrasing of an alternative conception came directly from a student statement. I used my own expertise and background knowledge to determine whether a heat transfer conception was scientific or alternative and whether a conception was applied correctly to the design challenge or not, and I also verified these conceptions and their application with literature about heat transfer conceptions (e.g., Lewis & Linn, 1994; Schnittka & Bell, 2011).

3.7.5 Segmenting the Data

After creating the coding frame, I segmented the data into units of coding. Units of coding are the parts of the data that a researcher "can meaningfully interpret with respect to the categories at hand" (Schreier, 2012, p. 131). For my purposes, each unit of coding was a statement said or written by one student about one specific heat transfer conception. A unit of coding is essentially an "instance," as referred to earlier. These units of coding allowed me to analyze the data set in terms of each conception for each student.

3.7.6 Coding the Data

For each unit of coding, or instance, I assigned it to sub-categories within each category of the coding frame (Schreier, 2012). An important note about the coding process was that I coded each instance as exactly stated by a student. I acknowledge that these students were in seventh grade, and therefore, it is likely that they sometimes misspoke or mis-wrote. For example, during Lesson 6, Marie wrote, “The similarities between conduction, convection, and radiation is that they all transfer light in some way.” As written, this statement is an alternative conception. However, Marie may have actually had the conception that they all transfer heat, which is a scientific conception, but for some reason she accidentally wrote “light” instead of “heat.” In order to consistently interpret the data, I chose to code each statement using the literal words stated by the students as a proxy for what they were thinking, even though this may not have been true for every single statement.

3.7.7 Analyzing the Students and the Team

After each unit of analysis was coded using the codebook, I analyzed students’ use of heat transfer conceptions throughout the unit across two levels, as recommended for embedded, single case study designs (Yin, 2014). One level of analysis was at the level of the embedded sub-units, which in this study were the individual students. The other level of analysis was the case, which was the student team. As explained in section 3.1, the results are primarily presented as the story of the case, or team, but individual analyses were highlighted when it made sense within the structure of the story to do so.

3.7.8 A Note About the Use of Certain Key Terms

During the analysis described above, I did not specifically consider how the students used certain key terms of the unit, including “temperature” but especially “heat.” For example, it did not matter if a student wrote, “pass heat off to,” instead of the more scientific “transfer heat.” Additionally, I did not consider when students used the term “heat” in place of the more correct “thermal energy” (e.g., “heat transfer” rather than “thermal energy transfer”), since experts often use “heat” in this way (Bauman, 1992). What mattered was the larger scientific or alternative conception represented by the statement.

Instead, I performed a separate analysis of certain key terms. First, I searched for students' use of the following terms: "cold," "colder," "coldest," "cool," "coolest," "degrees," "heat," "hot," "hotter," "hottest," "temperature," "thermal energy," "warm," and "warmer." Second, for each term, I analyzed how students used it in the statements. This analysis consisted of looking at how consistent students were with their semantic use of the terms. When the terms were used consistently, the analysis stopped. When the terms were not used consistently, I counted the frequency of each manner in which students used the term. The results of this analysis are presented in section 4.3.

3.8 Quality of Research Design

While the quality of quantitative research designs are judged by tests of validity and reliability, multiple tests for qualitative research designs exist (e.g., Creswell, 2013; Lincoln & Guba, 1985; Merriam, 1995). Depending on the research paradigm and qualitative research design used, these tests might include such terms as trustworthiness, credibility, triangulation, or crystallization. For this study, however, I have chosen to use three tests of quality proposed by Yin (2018): construct validity, external validity, and reliability.

3.8.1 Construct Validity

To meet the test of construct validity, a researcher must identify appropriate ways to measure the study topic's specific concepts (Yin, 2018). One way to establish construct validity is to collect multiple sources of evidence, which allows for triangulation of the data. When a finding is supported by the convergence of different types of evidence, that finding is essentially supported by multiple measures. In this study, I was able to collect and triangulate multiple sources such as audio and video of student conversations, observations and field notes, and pictures and copies of student artifacts. A second way to address construct validity is to establish a chain of evidence. This means that there must be clear linkages between: the case study report, the case study database, the evidence in the database (which includes how the evidence was collected), the data collection protocol, and the case study questions. I addressed this by maintaining a clear record of how I collected and analyze the data.

3.8.2 External Validity

External validity involves determining the generalizability of a study, or the extent to which a study's findings are applicable to other contexts (Merriam, 1995; Yin, 2018). One strategy for addressing external validity is to provide a "thick description" of each case (Merriam, 1995, p. 58). By providing detailed information about both the context and findings of the case, readers should be able to determine how closely their own settings match that of this study and thus determine whether the findings are applicable. Therefore, the results of the study are presented as a case with a detailed thick description in section 4.2.

3.8.3 Reliability

The test of reliability answers the question: If a different researcher were to repeat the study using the same procedures, would he/she arrive at the same conclusions? (Merriam, 1995; Yin, 2018). One method to address reliability is peer checking of the data, analyses, and results (e.g., Merriam, 1995). Thus, I asked a few of my committee members to check the plausibility of my interpretations of the data. For example, I asked a heat transfer expert to check my interpretations of students' science conceptions.

Yin's (2018) case study design tests of quality also include tests for internal validity. However, he has stated that internal validity is relevant only to explanatory case studies; since this study is descriptive, internal validity does not need to be addressed.

3.9 Role of the Researcher and Researcher Background

Due to my role as a semi-participant observer in this qualitative study, it is important to explain my own background and experiences that influence my worldview and potential biases. I believe that I have a unique perspective to bring to the study of this problem, since I have an unusual variety of experiences with engineering, pre-college education, and the specific topic of heat transfer.

I have several experiences with engineering and learning about heat transfer and thermodynamics. I have an undergraduate degree in materials science and engineering (MSE), eight months of experience working as a co-op engineer in a biomaterials department at an orthopedic company, and additional completed coursework in graduate-level MSE. Through two undergraduate design projects – one freshmen team project and one senior individual project – several summers as an undergraduate research assistant, and especially the co-op engineer experience, I gained a basic understanding about the work of engineers. Also, throughout those experiences, I focused on two specific concentrations within MSE: biomaterials and thermodynamics. While thermodynamics and heat transfer are often different subjects at the college level, they are based on foundational concepts that are the same at the middle school level. Thus, my passion for thermodynamics helped me understand the variety of conceptions students may have about temperature, thermal energy, and heat transfer.

I also have direct experience with pre-college science education. I was a high school chemistry and physics teacher for four years, and both of those courses addressed concepts related to heat transfer. During that time, I also spent summers working on a small team of lead teachers developing a district-wide science pacing/curriculum guide and assessments based on the state science standards. Through these responsibilities, I became experienced with developmentally appropriate expectations in science for K-12 students. I also saw firsthand some of the scientific and alternative conceptions my students had about heat transfer.

Since coming to graduate school, I have been able to merge my passions for engineering and pre-college science education. I have completed coursework for both a Master's degree in Science Education and a Ph.D. in engineering education. Additionally, I worked on the EngrTEAMS project, which focuses on pre-college engineering design-based STEM integration, for four and a half years. Through this project, I have had opportunities to do research that contributes to the area of pre-college STEM integration education, develop curricular units, and lead and assist with teacher professional development experiences. These opportunities include work I have done specifically with the *Ecuadorian Fishermen* unit. I co-led editing the curricular documents for their fourth iteration and planning and delivering PD experiences to the teachers who plan to implement the *Ecuadorian Fishermen* unit. Thus, I not only have experience with researching and developing general engineering design-based STEM integration curricula, but I also have extensive experience related specifically to the *Ecuadorian Fishermen* unit.

In sum, my variety of experiences is beneficial because I understand perspectives of engineers, pre-college science educators, education researchers, and curriculum developers. Additionally, I have an in-depth understanding of heat transfer concepts at the pre-college, undergraduate, and graduate levels.

3.10 Limitations

There are several limitations of this research. First, the sample size of one student team with four students is small, which limits the generalizability of the findings. However, this limitation is partially mitigated due to steps that were taken to make clear external validity, namely by providing a thick description so that readers can determine how transferrable the findings are.

Two other limitations are related to how well I was able to interpret students' conceptions about heat transfer. The first of these limitations is that I did not give students a pre- or post-test or pre- or post-interview to determine their individual conceptions about heat transfer, including temperature, thermal energy, and methods of heat transfer (i.e., conduction, convection, radiation). There are three reasons for this. First, Mr. Parker did not agree to this additional research being done in his class. Second, pre- and post-tests and interviews were not part of the *Ecuadorian Fishermen* curricular unit. Third, while a pre-test or pre-interview could have helped me understand the students' baseline conceptions about science content, these pre-unit interventions would likely have impacted students' use of science during the unit. For example, part of the *Ecuadorian Fishermen* unit's first lesson, in which students define the engineering problem, is for them to figure out what sorts of concepts they would need to learn about in order to design a successful solution. If I had given the students a pre-test or pre-interview, this would have likely primed them to think about heat transfer. However, by not giving students a pre- or post-test or pre- or post-interview, my ability to interpret their conceptions about heat transfer before and after the implementation of the unit was limited.

The second limitation related to students' science conceptions is that I also did not ask follow-up questions to more deeply probe their thinking during the implementation of the unit. Part of the goal of this descriptive case study was to observe the student team as they naturalistically participated in the engineering design-based STEM integration unit. Therefore, I tried to limit my interaction with the team for the most part. However, this meant that students frequently said or wrote statements that were related to science ideas but which did not clearly reveal their underlying heat transfer conceptions. Because of the naturalistic setting of the case study, I usually did not follow up with the students about these statements so that I could better understand what their underlying science conceptions were. (I also used the literal statements written or spoken by students, which assumed that their language was an accurate reflection of their thoughts and understandings, not a misspoken phrase; this was described in section 3.7.2.)

On the one hand, this situation more realistically reflects what would actually happen in a classroom, since a teacher cannot follow up with every statement made by students, especially when small group activities are prevalent. On the other hand, this situation somewhat limited my ability to interpret every single science statement in terms of the underlying science conceptions.

Another limitation related to the previous one was the semantic difficulties of heat transfer language, including the word “heat.” In this study, I attempted to determine students’ conceptions from their language in a science content area, heat transfer, that has inherently problematic language in addition to being conceptually challenging. “Heat” is commonly used to mean “thermal energy” (e.g., in the phrase “heat transfer”) in most settings including scientific ones, which presents an added layer of difficulty in my ability to interpret students’ underlying conceptions from the way that they use terms that are inconsistently used even by experts. This limitation also affected my ability to write about the results. Given that experts often use the term “heat” when the more correct term would be “thermal energy,” especially when coupled with other verbs (e.g., “heat transfer” instead of “thermal energy transfer”), I also follow that convention in the following chapters even though it is not the most scientifically correct nomenclature.

Another limitation was related to the affective domain. During this study, students’ personalities and daily moods affected their participation and interactions with each other, which therefore affected their learning. For example, Marie’s daily mood definitely affected her participation in the unit. For most of the unit, Marie was excited and thus participated eagerly and thoroughly. However, on the days that Marie was in a bad mood, she participated less in student team discussions and did not respond to all prompts in her engineering notebook; instead, she usually put her head on her desk or talked to a student on another team about unrelated topics. Another example has to do with student interactions. For various reasons, Marie and Noelle sometimes ignored Sheldon. At times, this was good for the team because Sheldon occasionally talked about unrelated topics, and paying attention to him would have distracted the whole team. At other times, however, Sheldon was trying to contribute scientific conceptions to the discussion; by ignoring him, Marie and Noelle missed a learning opportunity. In sum, students’ personalities and moods ultimately affected how many and what kind of heat transfer conceptions they spoke or wrote about.

CHAPTER 4. RESULTS: THE CASE

In this section, I describe the results which answer this study's research questions:

- During an engineering design-based STEM integration unit:
    - What scientific and alternative conceptions about heat transfer does a team of middle school students use?
    - How do engineering design, redesign, teamwork, and communication influence students' use of these conceptions?

Because of the complexity of the results, I first present a high level overview of the results that briefly describes what conceptions about heat transfer students used in different parts of an engineering design process. Then, I describe the case, which includes more detailed descriptions of students' conceptions about heat transfer, as well examples of student talk and writing to demonstrate these conceptions. The case description has three major parts, corresponding with the engineering design-based STEM integration unit layout: problem scoping, the first round of solution generation, and a second round of solution generation (i.e., redesign). After the case description, I focus on two specific results that are also relevant to the research questions. First, I describe how the student team used certain key terms, including "heat," throughout the unit. Second, I describe one student's participation, or lack thereof, in the unit, since Dylan had noticeably different participation when compared to her peers.

This chapter does not include a summary of the results at the end. Instead, the summary of results is included with the discussion in Chapter 5, with each section being organized by a component of the STEM Integration Framework.

4.1 Overview of the Case

An overview of the heat transfer conceptions used by students during specific stages of an engineering design process, steps of an engineering design process, and lesson of the *Ecuadorian Fishermen* unit is provided in Table 4.1. The parenthetical letters at the end of each conception represent who demonstrated the conception: Dylan (D), Marie (M), Noelle, (N), and/or Sheldon (S). Conceptions in *italic font* represent scientific conceptions. When a conception is *italicized* and also designated with an asterisk (*), that means that students correctly analyzed data from a laboratory activity to form the conception. In other words, they demonstrated a scientific conception about the practice of data analysis. Conceptions in underline font represent alternative conceptions used by students. If a conception is in regular font, that means that it was not necessarily a scientific or alternative conception. In some cases, students made a statement that was difficult to interpret, so the direct quote is included in the table in regular font. For example, Marie once wrote, “Conduction is through how thermal energy,” which is not complete enough to determine whether she was on track to demonstrate a scientific or alternative conception. In other cases, the student team made statements that were reasonable statements but not necessarily scientific or alternative conceptions about heat transfer. These statements in regular font are included because they help demonstrate students’ conceptions, even if they are not conceptions themselves.

One final note about Table 4.1 is that it only describes the conceptions used by students, not how the students used them to design engineering solutions. In other words, the table does not differentiate between students applying scientific conceptions correctly or incorrectly to the design of their prototypes. That information is described in more detail in the case in section 4.2.

Table 4.1. *Overview of results: Students' heat transfer conceptions throughout an engineering design process (EDP)*

EDP stage, EDP step	Lesson	Heat transfer conceptions used by students
Problem Scoping, Define (the problem)	1: Defining the Engineering Problem	• *Dark colors absorb radiation/light energy better than light colors* (M,N,S)
Problem Scoping, Learn (about the problem)	2: Temperature and Heat Transfer & Convection	• *Particles move faster when the temperature increases* (M,N,S) • *Adding heat can change the state of matter* (M,N) • *An object with a higher temperature has a larger value of degrees Celsius* (N,S) • *Thermal energy depends on the number of particles in an object* (N,S) • *The direction of heat transfer is from hotter objects (i.e., objects with higher temperatures) to colder objects (i.e., objects with lower temperatures)* (D,N,S) • *Hot fluids rise* (D,N,S) • *Fluid movement is related to density* (D) • *This process of heat transfer in fluids is convection* (N,S)

Problem Scoping, Learn (about the problem)	3: Heat Transfer Through Conduction	• *Materials at the same temperature can feel different because they transfer heat at different rates* (D,M,N)
		• Predictions for ice-melting conduction lab:
		  ○ *A material that feels colder will transfer heat faster (i.e., is a better conductor)* (S)
		  ○ Heat will transfer more slowly in heavier/more dense objects (M,N)
		• *The direction of heat transfer is from hotter objects (i.e., objects with higher temperatures) to colder objects (i.e., objects with lower temperatures)* (M,N,S)
		• *Heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* (D,M,N,S)
		• *Conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas* (D,M,N,S)

Table 4.1 continued

Problem Scoping, Learn (about the problem)	4: Heat Transfer Through Radiation, 5: Analyzing the Absorption Property of Materials	• Definitions of radiation:
		  ○ *Radiation is the transfer of heat across space in the form of light waves* (M,N)
		  ○ *Radiation is the way the sun's heat gets to* us (S)
		  ○ "Heat absorbing dark colors" (D)
		• *When a material absorbs radiation/light waves, the temperature of the material increases* (D,M,N,S)
		• *When a material reflects radiation/light waves, the light waves bounce off the material* (D,M,N,S)
		• *When a material transmits radiation/light waves, the light waves pass through the material* (M,N,S)
		• *Dark colors absorb radiation/light energy better than light colors*
		• Predictions for radiation lab:
		  ○ *Dark colors absorb radiation/light energy* (M,N,S)
		  ○ Aluminum foil will absorb radiation (D,N)
		  ○ *Light colors reflect radiation/light energy* (M,N,S)
		  ○ Black felt will reflect radiation (D)
		  ○ *Clear materials transmit radiation/light energy* (M,N,S)
		  ○ Wooden sticks will transmit radiation (D)
		  ○ Aluminum foil will heat up (in the radiation lab) because it is metal (and thus conducts heat) (M,N,S)
		• Analysis of radiation lab: materials that transmit
		  ○ *Clear materials transmit radiation/light energy* (M,S)
		  ○ White felt (N), Black paper (D)
		• Analysis of radiation lab: materials that absorb
		  ○ *(In general) Dark colors absorb radiation/light energy better than light colors* (D,M,S)
		  ○ *Light colors absorb more because they had larger temperature increase in the radiation lab** (N)
		• Analysis of the radiation lab: materials that reflect
		  ○ *Metals reflect radiation/light energy* (D,M,N,S)

Table 4.1 continued

Problem Scoping, Learn (about the problem)	6: Getting to Know the Context	• Analysis of the solar oven:
		  ○ Air will heat up in the solar oven (D,M,N,S)
		  ○ *Hot fluids rise and circulate in convection* (M,N)
		  ○ “So you can build a lid and the air won’t rise” (N)
		  ○ *Conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas* (N)
		  ○ *Radiation is the transfer of heat across space in the form of light waves* (M,N)
		• Predicting which method of heat transfer is most important for design
		  ○ Radiation (M,S)
		  ○ Conduction (N)
		• Quizziz online review activity, team averages:
		  ○ 46% correct on questions to which answer was “conduction”
		  ○ 50% correct on questions to which answer was “convection”
		  ○ 55% correct on questions to which answer was “radiation”
		• Similarities among methods of heat transfer:
		  ○ “Have something to do with heat” (D)
		  ○ “All produce/give heat” (N,S)
		  ○ “<u>All transfer light in some way</u>” (M)
		• Radiation:
		  ○ *Radiation is the transfer of heat across space in the form of light waves* (N)
		  ○ *Dark colors absorb radiation/light energy* (D)
		  ○ “Radiation is through sunlight” (M)
		• Conduction:
		  ○ *Materials at the same temperature can feel different because they transfer heat at different rates* (N)
		  ○ “Conduction is how heat energy transfers” (D)
		  ○ “Conduction is through how thermal energy” (M)
		• Convection:
		  ○ *Hot fluids rise and circulate in convection* (N)
		  ○ “Convection is through how the air transfers through liquids” (M)

Table 4.1 continued

Problem Scoping, Learn (about the problem)	6: Getting to Know the Context	• Whole class review ○ *Materials at the same temperature can feel different because they transfer heat at different rates; the direction of heat transfer is from hotter objects (i.e., objects with higher temperatures) to colder objects (i.e., objects with lower temperatures)* (M) ○ *Heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* (S)
Solution Generation Part 1: Initial Design, Plan (a solution)	7: Exploring Materials and Planning: Idea Generation, 8: Planning: Idea Selection and Evidence-Based Reasoning	• Thermal properties of materials review (at first): ○ *Materials at the same temperature can feel different because they transfer heat at different rates* (M,N,S) ○ *A material that feels colder will transfer heat faster (i.e., is a better conductor)* (M,N,S) ○ *Heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* (M,N,S) • Thermal properties of materials review (later): ○ White felt is a good conductor because it had the highest temperature increase (during the radiation lab) (D,M,N,S) ○ Aluminum foil is a good insulator because it had the lowest temperature increase (during the radiation lab) (M,N,S) ○ *Metals reflect radiation/light energy* (M,N,S) ○ *Dark colors absorb radiation/light energy* (M) ○ White felt is an insulator "because insulation is always a light color" (S) ○ *Radiation is the transfer of heat across space in the form of light waves* (M,S) ○ *Conduction is the transfer of heat energy through a solid* (M) ○ *When a material keeps an ice cube solid for a longer time, that material is an insulator* (S) ○ Aluminum foil is a good insulator because it keeps ice solid longer (N,S) ○ "This one [white paper] would be a conductor" (N) ○ *Wood is an insulator* (M)

Table 4.1 continued

Solution Generation Part 1: Initial Design, Plan (a solution)	7: Exploring Materials and Planning: Idea Generation, 8: Planning: Idea Selection and Evidence-Based Reasoning	• Individual design idea generation: ○ *Heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* (D,N,S) ○ Transparency sheet is a good conductor because it had a high temperature increase (during the radiation lab) (D) ○ Aluminum foil is an insulator (D) ○ Black felt is a conductor (D) ○ *Dark colors absorb radiation/light energy* (M) ○ *White felt, transparency sheet, and black felt had the largest temperature increases during the radiation lab** (D,M,S) ○ *Metals reflect radiation/light energy* (M) ○ *Clear materials transmit radiation/light energy* (S) ○ Aluminum foil absorbs radiation/light energy (D,S) ○ Wood absorbs radiation/light energy (N) • Team design select and evidence-based reasoning ○ *Radiation is the transfer of heat across space in the form of light waves* (M,N,S) ○ *Heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* (N,S) ○ *Black felt is an insulator* (N) ○ *White felt and transparency sheet had the largest temperature increases in the radiation lab* (M,N,S) ○ *Dark colors absorb radiation/light energy better than light colors* (M,N) ○ Wood absorbs radiation/light energy (N) ○ Transparency sheet reflects or absorbs radiation/light energy (M) ○ "The foil conducts the light" (N) ○ "The black and white felt absorb the light that the foil conducts" (N) ○ "All the heat and light that is radiating to the foil and felt will absorb and conduct to the fish" (M,N)

Table 4.1 continued

Solution Generation Part 1: Initial Design, Try (the plan of the solution)	9: Trying, Building the First Prototype	• *Heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* (M,N) • *Black felt is an insulator* (M,N) • White felt is a good conductor (M) • *Dark colors absorb radiation/light energy* (M,N) • *Metals reflect radiation/light energy* (M) • *Clear materials transmit radiation/light energy* (M,S) • Wood absorbs radiation/light energy (N) • Walls are “too thick” (N) • *Hot fluid rise* (N)
Solution Generation Part 1: Initial Design, Test (the solution) & Decide (about whether the solution is successful)	10: Testing and Deciding About the First Prototype	• First prototype increased only 14°C (control increased 16°C) • *Hot fluids rise* (S) • *Heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* (D,M,S) • *Conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas* (D,S) • Copper wire transfers heat quickly regardless of context (i.e., no distinction between conduction and radiation) (M) • *More layers of material (i.e., thicker) are insulating because heat transfer via conduction is more difficult* (M,N) • Wood is a good conductor (M,S) • Transparency sheet is a good conductor (M) • *Dark colors absorb radiation/light energy* (M)

Table 4.1 continued

Solution Generation Part 2: Redesign, Plan, Try, Test, & Decide	11: Redesigning a Second Prototype	• *Heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* (D,M,S) • *Conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas* (S) • Copper wire transfers heat quickly regardless of context (i.e., no distinction between conduction and radiation) (M,N) • *More layers of material (i.e., thicker) are insulating because heat transfer via conduction is more difficult* (M,S) • Walls of 1st prototype were "too thick" (M,N) • *The cooker container with transparency sheet top and sides had the largest temperature increase during prototype testing** (M,N,S) • *Dark colors absorb radiation/light energy* (D,M) • *Hot fluids rise* (N,S)
Communicate	12: Communicating with the Client	• *Heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* (D,M,N,S) • *Conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas* (D,S) • Copper wire transfers heat quickly regardless of context (i.e., no distinction between conduction and radiation) (M,N) • *Dark colors absorb radiation/light energy* (D,N,S) • *Clear materials transmit radiation/light energy* (S) • "Transparency sheets worked well because they are good at radiating heat" (N) • "I chose the transparency sheet because it gets to the highest" (M) • Walls of 1st prototype were "too thick" (M,N)

There are two main results from Table 4.1. First, the student team used many conceptions about heat transfer throughout the unit. Second, the team tended to use mostly scientific conceptions during the learn (about the problem) lessons, especially Lessons 2-5. As they began to think about all of the heat transfer conceptions in Lessons 6 and 7, they used a greater mix of alternative and scientific conceptions; this mix continued through the first round of solution generation. Then, starting in the decide (about whether the solution is successful) step and continuing through the second round of solution generation, the student team had the opportunity to learn from what happened during the first round of solution generation, and they thus used more scientific conceptions than alternative conceptions.

4.2 The Case – A Student Team's Participation in an Engineering Design-Based STEM Integration Unit

In this section, I provide a detailed, thick description of the case. This includes what heat transfer conceptions were used, how the students used them, and other details about the surrounding context. From this point forward, I describe my role in the case from the third person perspective, referring to myself as "the researcher" or "Researcher," in order to maintain a focus on the actions and statements of the student team.

4.2.1 Problem Scoping

The problem scoping stage of the *Ecuadorian Fishermen* curricular unit was comprised of two steps of an engineering design process: define (the problem) and learn (about the problem). Mr. Parker's implementation of Lesson 1: Defining the Engineering Problem took a little over three class periods to implement. The science content-focused lessons made up the learn (about the problem) step of an engineering design process. These five lessons were implemented over approximately seven days of class time.

4.2.1.1 Lesson 1: Defining the engineering problem.

During the first step of the engineering design process, defining the problem, students learned about several key parts of the engineering problem that they were to solve as engineers. Heat transfer was related to one of these key parts, and thus the student team used a few heat transfer ideas and vocabulary terms. Specifically, they used heat transfer ideas and vocabulary when they asked the client questions about the problem, defined one of the key criteria of the problem, and thought of what they might need to learn in order to design a successful solution.

The first time that heat transfer vocabulary was used to define the problem was when the students were given a chance to ask the client questions. Before this activity, students had read a letter from their client, the Pescadores Foundation, and watched a video of a fish market in Ecuador. These resources gave them information about the engineering problem and the challenge presented to them. The engineering problem was that fishermen in Ecuador sold raw fish at the fish market and wanted to sell cooked fish also. To solve this problem, the specific engineering challenge was for the students to design inexpensive prototype cooker containers that could hold fish and be placed in a solar oven to cook the fish. After the student team correctly identified the client, end user, and engineering problem, they were given a chance to generate questions for the client in order to better understand their engineering challenge.

All four members of the student team individually generated and recorded two to three questions for the client, most of which were relevant to the challenge but not related to heat transfer ideas. For example, Sheldon and Noelle asked how many fish the container would need to hold, Marie and Sheldon asked what size it would need to be, and Noelle asked how cheap or expensive it could be. Two of the team members asked questions related to temperature. In their notebooks, Noelle wrote, "How hot does it need to be?", and Marie wrote, "What temperature?". When the student team met to discuss the questions they had generated, Marie further clarified her idea by telling her teammates that one of her questions for the client was, "What temperature does it cook fish in?" The team agreed that was a good question to ask.

During the team discussion about what questions they should ask the client, the team also inquired about how fish can be cooked. For example, they asked each other if fish are usually fried, or if they could skewer fish on sticks and cook them over a fire. The student team also discussed using hot cars as a cooking method.

Noelle: What if you could just... So you know how hot cars get? They could just lay them on the car. It's been in the sun all day! *(laughs)*
Marie: They don't do that.
Sheldon: In the video, they were mostly white vehicles.
Marie: They need a black one, yeah, you need a black-
Noelle: Yeah, just spray paint it black.

Here, the team members referred to a scientific conception about heat transfer, that *dark colors absorb radiation/light energy better than light colors*. In this case, they related that conception to their personal experiences with how hot cars of different colors become when they sit in the sun.

After this small group discussion, the whole class was given a chance to ask the client questions. Mr. Parker answered the students' questions based on suggested responses in the *Ecuadorian Fishermen* curricular documents. He then introduced the students to the new terms "criteria" and "constraints" and had the students individually generate ideas about what the criteria and constraints of this problem were. The student team generated criteria and constraints such as needing to fit in the solar oven (Marie and Sheldon), needing to be cheap/within budget (Sheldon and Noelle), and needing to cook the fish (Marie and Noelle). Next, the student team met as a group to discuss their ideas.

During discussion, the students used heat transfer vocabulary to more specifically define one of the criteria; this use of heat transfer is the second use of heat transfer vocabulary and ideas when students defined the problem. After Noelle shared her idea that the fish needs to cook in the container, the researcher asked the team to clarify what they meant by "cook." During the question and answer session, the client had given the students a definition of "cooking" that was needed for their prototype designs, which was to maximize the temperature increase of the fish when the cooker container is placed in the solar oven for 10 minutes. After being prompted by the researcher, Sheldon responded, "The one that gets the highest, the hottest in 10 minutes." All members of team then rewrote the criterion of "cooking" as variations of "warming up" the fish.

The third activity in which students discussed and wrote about heat transfer vocabulary and ideas was in the final activity of the lesson. Students were given the prompt

> Think about the problem of cooking fish in a solar oven. In terms of being able to properly cook a fish using a cooker container in a solar oven, what are at least two things you need to learn in order to design a successful cooker container prototype?

Similar to other activities in the lesson, students were given time to answer individually in their engineering notebooks, then discuss their answers as a team, and finally write agreed-upon team answers in their notebooks.

When individually writing answers to the prompt, three of the four students on the team wrote at least one question explicitly related to heat transfer. Sheldon and Marie both wanted to learn about the temperature of the solar oven, with Sheldon writing, "How hot does the solar oven get?" and Marie asking, "What temperature does it heat up to?" Dylan also thought about the solar oven temperature but from a perspective of controlling it, writing, "How to make oven temperatures" and "How to make it stop." Finally, Marie began to think about possible materials, writing, "What different object's heat up?"

During the team discussion about what they wanted to learn, the student team discussed a variety of ideas, some more relevant to the problem than others. One relevant idea was related to thermal properties of materials. When Marie shared her idea about materials, "What different types of objects make the solar oven heat up faster?", Sheldon wrote "What materials heat up faster?" in his engineering notebook.

In contrast, two ideas related to heat transfer also demonstrated a lack of understanding about the problem and context. For the first idea, Marie asked Dylan to start the conversation, so Dylan began with, "How to make the oven temperatures and how to make it stop so it doesn't overcook it, the thing [fish]." Noelle and Marie agreed that overcooking could be a problem, and they began to think about adding a timer of some sort. Sheldon rebutted this idea, pointing out, "See but that would have to be connected to the solar oven, not the container." Noelle and Marie ignored his comment and added "How to make it stop so it won't overcook" to their list of what they need to learn. In this case, the three students were referring to their previous experiences with ovens, which can be set to a specific temperature and need a timer to prevent overcooking. However, Sheldon was the only one to realize that in the context of their specific engineering challenge, they were not designing a solar oven but rather a container that went inside it.

For the second idea, the team discussed how the solar oven worked. Noelle said that the solar oven might only work when the sun is out, and Sheldon said, "Because it keeps the energy from the sun so you can use it overnight and when the sun doesn't come out." This discussion prompted the team to realize that they needed to know more about the solar oven, and Marie, Sheldon, and Noelle all added questions to their notebooks about the type of solar oven or kind of solar power used. Here, the student team was using their previous knowledge about solar panels and solar energy being stored, but it is clear that they did not fully understand what a solar oven was in the context of the problem.

4.2.1.2 Lesson 2: Temperature and heat transfer & convection.

There were three major classroom activities in Lesson 2 of the *Ecuadorian Fishermen* curricular unit, and the student team used at least one heat transfer conception in each activity. In all three of these activities, there was no small group portion, so all evidence of heat transfer vocabulary and ideas from this lesson are from the students' engineering notebooks. Another important note about this lesson is that Marie was absent for the second and third activity; therefore, she has no notebook entries for these two activities.

In the first activity, students observed a computer simulation of particles in three states of matter: solid, liquid, and gas. All four students on the team recorded fairly accurate drawings of the particles in the three states of matter, as well as descriptions of how the particles moved in those states. Mr. Parker then adjusted the simulation to "heat" each state of matter, and the students observed what happened to the particle motion as the temperature increased. The student team's answers are in Table 4.2.

Table 4.2. *Students' notebook entries responding to the prompt "What happens to the particles when the temperature increases?"*

Student	Notebook entry
Marie	1 [solid] – the particles started to move faster 2 [liquid] – the particles started to lift up and rise 3 [gas] – they started bumping into each other and moving really fast
Sheldon	They move around faster.
Noelle	When you add heat the particles move faster and melt into another state of matter.
Dylan	*Wrote the prompt but did not answer it*

Although Dylan did not write an answer to the prompt, the other three student team members identified the scientific conception that *particles move faster when the temperature increases*. They had not yet learned that temperature is a measure of particle motion, but they correctly observed the relationship between degree of temperature and motion of particles. Additionally, Marie and Noelle noted changes of state. Marie described the particle motion of a vaporization change of state, writing "the particles started to lift up and rise," while Noelle directly referenced a state change by writing that the particles "melt into another state of matter." These statements are limited in detail, but they are both related to the scientific conception that *adding heat can change the state of matter*.

In the second activity of Lesson 2, students learned about temperature, thermal energy, and heat. They watched a *Eureka* video about “Temperature vs. Heat.” In this animated video, the narrator discussed using a bucket of 50°C water or a cup of 100°C water to heat up two pools of cooler water. Although the water in the cup had a higher temperature, the water in the bucket better increased the temperature of a pool because it had a larger “quantity of hotness,” or “heat,” due to the additional molecules of water. After the video, Mr. Parker clarified to the whole class that whenever the narrator used the word “heat” in the video, he should have been used the term “thermal energy.” Mr. Parker then gave the students definitions for temperature, thermal energy, and heat, shown in Table 4.3, which the students copied into the Vocabulary section of their notebooks.

Table 4.3. *Definitions for temperature, thermal energy, and heat given to students*

Term	Definition
temperature	A measure of the average kinetic energy (KE) of particles of matter
thermal energy	The total amount, or sum, of kinetic energy in a substance; it depends on temperature and total number of particles
heat	The thermal energy transferred from one object to another due to the temperature difference between the objects; energy is transferred from hotter objects to colder ones

While presenting the key terms, Mr. Parker also led a whole class discussion about kinetic energy, which the students had learned about in an earlier science class.

The students then did a worksheet, individually first followed by a whole class discussion, in which they could apply the key terms. The worksheet showed two touching blocks made of the same material, with the larger Block 1 at a temperature of 25°C and the smaller Block 2 at a temperature of 30°C. The students were asked to write which block had a higher temperature, which block had more thermal energy, and which direction heat transfer (i.e., a transfer of thermal energy) will occur.

For the first question about the blocks, Sheldon and Noelle both correctly identified that Block 2 had a higher temperature. Sheldon wrote, “Block 2, because it is hotter than Block 1,” and

Noelle wrote, “Block 2 because Block 1’s temperature is 25°C and Block two’s is 30°C.” Both justified their choice, with Noelle directly referring to specific temperatures and Sheldon referring to hotness. Dylan initially wrote “Block 1” when she answered the question individually, but during the following whole class discussion, she changed her answer to “Block 2” but did not include any further explanation. Given these final answers, the students on the team were able to correctly use the conception that *an object with a higher temperature has a larger value of degrees Celsius*.

For the second question about the blocks, Noelle and Sheldon again correctly identified that Block 1 likely has a higher thermal energy, even though it has a lower temperature. Both Sheldon and Noelle explained their choice of Block 1 by saying that it “has more particles than Block 2.” Again, Dylan initially wrote the incorrect answer, Block 2, but then changed her answer to “Block 1” during the whole class discussion. The scientific conception demonstrated by Noelle and Sheldon’s answers to this question is that *thermal energy depends on the number of particles in an object*. Although this is not a complete conception since thermal energy also depends on the temperature of an object, it is partially correct.

For the third question about the blocks, all three students on the student team correctly identified that the direction of heat transfer would be from Block 2 to Block 1. Sheldon supported his choice by writing, “because Block 2 is hotter,” and Noelle and Dylan both wrote that Block 2 “has a higher temperature.” Additionally, Dylan wrote, “and so heat will start there” when referring to Block 2. It was unclear whether Dylan wrote this answer during the individual work time or during the follow-up whole class discussion. Based on these answers, the student team correctly applied the scientific conception that *the direction of heat transfer is from hotter objects (i.e., objects with higher temperatures) to colder objects (i.e., objects with lower temperatures)*. It is unclear from their answers whether the students were distinguishing between “thermal energy” as a quantity and “heat” as a process of thermal energy transfer, but they still were able to correctly identify the direction of the transfer process.

The class then moved on to the third activity of Lesson 2, which was about convection. The students watched an animated *Eureka* video about “Convection,” which discussed the process of convection and how it is related to the density of fluids. The students then observed a teacher demonstration about convection. The teacher placed some gel food coloring on the bottom of a clear tub of water. The tub of water was elevated so that a heat source, in this case a cup of boiling water, could be placed under the gel food coloring. This demonstration was structured so that students could predict, observe, and explain what happened in the tub.

Mr. Parker explained the demonstration first and asked the students to predict what would happen once the heat source was applied underneath the food coloring in the plastic tub of water. All three student team members present had reasonable predictions with Dylan predicting that "it will mix all around" and Sheldon and Noelle specifically focusing on the direction of mixing. Noelle wrote, "the food coloring will rise to the surface of the water," and Sheldon wrote, "I think we will see the water go up then down and repeat." Mr. Parker then applied the heat source, and students watched as the food coloring slowly rose in the water from the bottom of the tub, spread out along the top, and descended near the sides of the tub of water. The students then wrote their observations, with Noelle and Dylan writing about the food coloring rising and Sheldon noting that it "went up and then down."

Mr. Parker then asked the students to explain their observations in their notebooks. Noelle did not write an explanation. Sheldon wrote, "It happened because the warm water goes up and the cold water goes down." This explanation is a correct statement, though it does not explain the underlying reasons related to the density and temperature of the water. In contrast, Dylan did specifically mention density, writing, "This happened because of the hot water makes it less dense." It is evident that she used the scientific conception that *fluid movement is related to density*, even though she did not explain that relationship.

Finally, the students were supposed to identify this process of heat transfer. They copied the text, "The process of heat transfer this represents is:" into their notebooks and then asked to complete the sentence. Sheldon correctly wrote "convection," and Dylan incorrectly wrote "liquid." Noelle initially wrote, "thermal energy," but then changed her response to "convection." Here, there was confusion about the exact term needing to be used, convection. Also note that Mr. Parker chose to keep this key term only in the main body of their notebooks; students did not add "convection" to the Vocabulary section of their engineering notebooks.

From the evidence provided in this third activity, it seems that the students had a mix of conceptions about convection. With their predictions, observations, and Sheldon's explanation, they seemed to understand the scientific conception that *hot fluids rise*. However, only Dylan mentioned density, the underlying reason for this phenomenon. Also, only Sheldon and Noelle correctly identified the process as "convection." This evidence indicates an incomplete understanding of convection.

4.2.1.3 Lesson 3: Heat transfer through conduction.

In Lesson 3, the class did two inquiry-based activities related to conduction and ended with Mr. Parker formally introducing the key terms of "conduction," "conductor," and "insulator." The student team used several different heat transfer conceptions during the two activities, and in some instances their conceptions changed as a result of the activities.

The first activity was designed to address a common alternative conception, which is that how an object feels to the touch is a measure of that object's temperature. Mr. Parker asked the students to place one hand on a wooden desk leg and the other hand on a metal chair leg. Students then identified, first in their notebooks and then as a whole class, which material felt colder and which felt warmer. All four students on the student team agreed that the metal chair leg felt colder than the wooden desk leg. Mr. Parker then used an infrared thermometer to measure the temperature of the two furniture legs, as well as several other objects in the room. He operated the thermometer but asked several students, including Dylan and Noelle, to read the results of the measurement aloud to the class. After Dylan and Noelle read that the temperatures of the wooden desk leg and metal chair leg were both 22°C, several students in the class expressed surprise, saying, "What?!" Mr. Parker then measured the temperatures of the ceiling and the white board at the front of the room, which were also both 22°C. Students continued to express confusion, with Sheldon asking, "Is that thing accurate?" Mr. Parker asked the whole class why these objects felt different even though they were at the same temperature. The class agreed that it must be related to the materials themselves, and Sheldon offered an idea that, "It [the chair leg] is more dense than the [wooden] table leg." Mr. Parker continued to accept other ideas about why the materials felt different before attempting to answer the question.

To help explain to the students why some materials feel colder or warmer even though they are the same temperature, Mr. Parker showed a *Veritasium* video, "Misconceptions About Temperature," that presented a similar experiment to adults. The narrator asked adults to feel a metal hard drive and a paper book and then say which was colder. Everyone in the video said the metal hard drive was colder and then were surprised when the two objects were measured to be the same temperature. The narrator then asked the adults to feel a plastic block and aluminum block and predict which one would melt ice faster. The adults said that since the aluminum block felt colder, the ice on it would melt slower. The narrator placed ice on the two blocks, and again the adults were surprised when the ice on the aluminum block melted faster. When asked to explain why, the adults struggled to answer. Finally, the narrator explained that materials feel different because they have different thermal conductivities, which is related to the rate at which heat is transferred. When people touch an object with a higher thermal conductivity, it transfers heat away from or toward their hands faster than an object with a lower thermal conductivity. The former materials also conduct heat to an ice cube faster, melting it faster.

After the class watched the video, they wrote in their engineering notebooks to answer the question, "Why do metals feel colder than items such as plastic, wood, or paper?" Sheldon wrote, "The chair leg is more dense than the table leg." Although this was a correct comparison of densities, it was not the best explanation for why different objects feel like they have different temperatures. Marie, Dylan, and Noelle had more correct answers that were about transferring heat. Marie wrote, "the metal chair felt colder because of the absorption of heat," Dylan wrote, "It absorbs the heat from your hand," and Noelle wrote, "The metal transfers heat better than the wood." All three of these answers are rooted in the scientific conception that *materials at the same temperature can feel different because they transfer heat at different rates*.

In the second inquiry-based activity, students explored how different materials melted ice more quickly or slowly. First, Mr. Parker gave each team two blocks of the same volume, one metal block and one wood or polymer block. He asked the teams to predict which one would melt ice faster if ice cubes were placed on top of the blocks, similar to the experiment done in the *Veritasium* video. The student team received one brass block and one rosewood block.

During the small group discussion about their predictions, Dylan, Sheldon, and Noelle predicted that ice would melt faster on the brass block, while Marie thought it would melt faster on the rosewood block. The students provided different reasons for their predictions. Sheldon's reason was related to the *Veritasium* video. He started the team discussion by saying, "I think it's going to melt fast on this one [brass] because this one's colder." Based on this and other similar statements, Sheldon had combined the two experiments in the video to create his own heuristic that *a material that feels colder will transfer heat faster (i.e., is a better conductor)*. Based on the information presented in the video, this was a useful heuristic and a *scientific conception*. Dylan agreed with Sheldon that ice would melt faster on brass, but her explanation of why was not audible.

Noelle and Marie both seemed to have underlying justifications related to density and size, though their explanations were less clear. These reasons can be seen in the following team discussion, which occurred when students were predicting.

Sheldon:	I'm gonna say brass.
Noelle:	So I say brass because…
Sheldon:	Cause it's gonna bring the heat out faster.
Noelle:	Yeah, heat travels better in that [brass], I would say. Well, unless the type of wood, and I feel like it [wood] is more dense.
Marie:	Well, I say this one [rosewood].
Researcher:	Because?
Marie:	Because it's not, the heat's gonna come out faster than this big old thing [brass].
	(Unrelated discussion)
Noelle:	Because that one [rosewood], that one is more dense, I feel like, so heat won't travel as fast in it.

Here, Marie, Sheldon, and Noelle discussed that heat will "come out faster" or "travel better" in different materials. Marie did not think the heat will transfer faster in "this big old thing [brass]." Given that the two blocks had the same volume, it can be inferred that "big" refers to the mass or weight of the brass block. In other words, Marie's prediction that ice will melt faster on rosewood was based on an alternative conception that <u>heat will transfer more slowly in heavier objects</u>. Noelle also based her prediction on density, though her ideas were less clear. She stated that wood is denser than brass, and thus heat will not travel as fast in the rosewood. Her prediction seems to be based on the same underlying alternative conception as Marie, that <u>heat will transfer more slowly in more dense objects</u>. However, because Noelle incorrectly identified rosewood as being denser than brass, she made the opposite prediction as Marie, which was that the ice would melt faster on brass. This prediction was correct despite her two incorrect conceptions.

After the students wrote their predictions in the engineering notebooks, Mr. Parker passed out two ice cubes to each team. The students then placed the ice cubes on top of their two materials and observed what happened. The ice cube on top of the brass block melted much quicker than the ice cube on the rosewood block. Although Marie acknowledged these observations, she resisted the idea that her prediction was incorrect. For example, she once picked the ice cube up off the rosewood block and said to it, "Come on, faster," and another time started to breathe heavily on that ice cube in an attempt to make it melt faster. After Marie repeatedly said, "It's not fair," and, "The ice cube is rigged," the rest of the team proposed switching the ice cubes. They did this and noted that the ice cube now on the brass block, formerly on the rosewood block, started melting quickly. Ultimately, Marie agreed that the ice melted faster on the brass block, though she was unhappy that her prediction was incorrect.

While the students were waiting for the ice to melt, Noelle extended what she was learning about conduction to previous life experience.

Noelle:	Okay, so the Yetis. So they're made out of metal.
Researcher:	They are.
Noelle:	So why wouldn't, so they keep. My mom has left her Yeti cup in her car over the summer for two days, and the ice was still in there. But if it's, heat travels fast through metals, why won't, why won't the ice melt faster?
Sheldon:	It's cause the Yeti has, is uh…
Researcher:	So the question is: is it just metal?
Sheldon:	No, it has insulation on it, in it.

Noelle had thought of a contradiction between what she was learning, that heat travels fast through metals, and her experience with a highly insulating metal Yeti cup. After guiding questions from the researcher, Sheldon and Noelle agreed that there must be some insulating material between the metal walls of the Yeti cup. Otherwise, as Noelle later said, "If this [Yeti cup] was solid metal, it would probably melt really fast." Here, Noelle and Sheldon used conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* to resolve a seeming contradiction between an everyday experience and the science concept.

Another discussion that occurred as students waited for the ice to melt on the blocks was prompted when the researcher tried to relate the science lesson back to the engineering prompt.

Researcher:	What step are we at right now?
Marie:	Learn!
Researcher:	Learning! Why are we learning?
Sheldon:	Cause we're learning about ice! No, I mean, about heat transfer.
Researcher:	And why do we care about heat transfer? Why do we need to learn about that?
Marie:	Because it's science.
Sheldon:	Because we need to learn about what materials get hot faster.

Here, Sheldon was able to identify that one of their goals for learning about heat transfer was "to learn about what materials get hot faster." He made a connection between the science lesson and the larger engineering challenge.

After the teams observed the two ice cubes melting, they were given the following instructions:

> Draw a diagram showing each material with an ice cube on top. On the diagram, indicate the direction of heat transfer using arrows. Also, note which material transferred heat more quickly.

All four student team members drew the two blocks with ice cubes on top. However, Dylan did not draw anything else. However, the remaining team members correctly drew arrows upwards, from the blocks to the ice cubes, to show the direction of heat transfer. This direction of arrows is based on the scientific conception that *the direction of heat transfer is from hotter objects (i.e., objects with higher temperatures) to colder objects (i.e., objects with lower temperatures)*. Also, Marie, Noelle, and Sheldon all correctly labeled the brass block as "transferring heat faster."

After drawing their observations, Mr. Parker asked each student team to share the material, out of their two materials, on which the ice melted the fastest. The whole class discussed these results and noted that for every team, the ice melted faster on the metal blocks than the plastic or wood blocks. Students recorded this result in their engineering notebooks.

Next, Mr. Parker asked the students to individually write an answer to the prompt, "Why did the ice melt faster on certain surfaces?" All four students' answers were about heat transferring faster on metals. For example, Dylan wrote, "Because heat transfers faster on those surfaces [metal]." Noelle went a step further and used the term "conductor," writing, "Some melted faster because they are faster heat conductors." Given that the terms "insulator" and "conductor" had not yet been formally introduced as key terms, it is not surprising that the other students did not use them. Based on their answers to this prompt, as well as their drawings mentioned previously, all four students seemed to have some understanding of the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*.

After these two inquiry-based activities, Mr. Parker introduced the terminology and explanations of conduction, conductors, and insulators. The class watched a *Eureka* video about "Conduction," which explained conduction in terms of atomic vibrations and that metals are good conductors because they have free electrons that can quickly transfer energy. After the video, Mr. Parker provided students with definitions for "conduction," "conductor," and "insulator," which students wrote in the Vocabulary section of their engineering notebooks. For example, they wrote that *conduction is the transfer of heat energy through a solid or from a solid to another solid,* *liquid, or gas*. Finally, he related these ideas back to the engineering challenge, leading a discussion about which materials might be useful or not to provide conduction in their cooker containers. Marie participated in the discussion, providing a response of "plastics" when Mr. Parker asked which materials they might want to avoid using. Although Marie had initially thought that plastics or wood might be better at transferring heat, this statement along with her engineering notebook suggest that she understood that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*.

4.2.1.4 Lesson 4: Heat transfer through radiation and Lesson 5: Analyzing the absorption property of materials.

Although Lesson 4 and Lesson 5 are distinct lessons in the *Ecuadorian Fishermen* curricular unit, they were both related to the heat transfer process of radiation and are thus best described together. In Lesson 4, students were introduced to and wrote their ideas about key terms related to radiation. They then collected data in a radiation lab. In Lesson 5, students analyzed these data graphically to compare how various materials absorb, reflect, and transmit radiation. These activities across the two lessons, as well as the heat transfer conceptions students used within them, are described in this section.

In the first activity of Lesson 4, students were introduced to the concept of radiation as a method of heat transfer. Mr. Parker asked the whole class about the major source of radiation that would tie to the engineering challenge, students identified the sun. Mr. Parker then asked the class if anyone knew how the sun heats up the Earth, but no one answered. He then showed students a *Eureka* "Radiation" video, which first reviewed conduction and convection before describing radiation. The video described radiation as waves of heat energy, or light, that can make molecules move and be hotter, which explains how the sun heats up the Earth. Mr. Parker then led a whole class discussion about the students' experiences with various materials absorbing, reflecting, and transmitting light. At one point, Sheldon participated in the discussion.

Mr. Parker:	So think about in the summertime especially, so in the summertime, what would we imagine would get warmer, a car with a dark interior or a car with a light interior?
Sheldon:	A car with a dark interior.
Mr. Parker:	Why?
Sheldon:	Because the sun's attracted, well the heat is attracted to the darker colors.

Mr. Parker: So let's be careful with the word, attracted. Can you think of a different word that might make a little bit more sense?

At this point, Mr. Parker called on another student, who used the term "absorb." Mr. Parker reinforced this terminology, saying, "A dark colored material would absorb that energy." Though Sheldon's phrasing of heat being "attracted" to darker colors was corrected, he based his idea on a scientific conception that *dark colors absorb radiation/light energy better than light colors*.

After the video and whole class discussion, the students individually wrote in their notebooks. They first defined "radiation" in their own words. Marie and Noelle both defined radiation in terms of waves, with Marie writing, "Radiation is heat waves that transfer through space," and Noelle writing, "Radiation are waves that people cannot see; there are multiple causes of radiation like heat." Both of these ideas are based on the scientific conception that *radiation is the transfer of heat across space in the form of light waves*. Sheldon's definition of radiation was, "the way the sun's heat gets to us," which is a true fact about radiation but not necessarily a definition of radiation. Dylan defined radiation as, "Heat absorbing dark colors." Although dark colors absorbing heat is part of radiation, it is lacking as a definition.

Mr. Parker then prompted students "to describe and/or draw what happens when light waves interact with a material that a) absorbs light, b) reflects light, and c) transmits light." Sheldon and Marie both chose to draw these interactions. Figure 4.1 shows Sheldon's drawings.

Figure 4.1. Sheldon's response to the prompt, "draw what happens when light waves interact with a material that a) absorbs light, b) reflects light, and c) transmits light."

Sheldon chose to use everyday objects in his drawings, using a dark colored shirt for absorbing light, a light colored shirt for reflecting light, and a window for transmitting light. Marie's drawings were similar to Sheldon's, though she chose to use blocks and lines rather than everyday objects and arrows. Noelle and Dylan responded to the prompt in words. For absorbing light, Dylan wrote, "It would get hotter on that light," and Noelle wrote, "When light waves interact with something that can absorbs light and heats up." Also, Marie labeled her absorption drawing as "hot." Hence, the responses given by Dylan, Noelle, and Marie imply that they understood the scientific conception that *when a material absorbs radiation/light waves, the temperature of the material increases*. Although Sheldon did not explicitly show that conception in his drawing, he used a similar idea when participating in the previous whole class discussion. For reflecting light, Dylan wrote, "shine back," and Noelle wrote, "When light waves interact with something that can reflect light it bounces off." None of the four discussed how reflecting light would affect an object's temperature, but their drawings and descriptions demonstrate the scientific conception that *when a material reflects radiation/light waves, the light waves bounce off the material*. Finally, for transmitting radiation, Dylan did not write anything, and Noelle wrote, "When light waves transmits lights it will go right through." For this final key term, Sheldon, Marie, and Noelle's responses indicate an understanding of the scientific conception that *when a material transmits radiation/light waves, the light waves pass through the material*. In sum, the student team mostly had appropriate scientific conceptions about absorbing, reflecting, and transmitting light.

The second activity of Lesson 4 was the prediction and data collection portion of the radiation lab. For the prediction portion, Mr. Parker presented the eight materials that would be used in the radiation lab: black and white construction paper, black and white felt, aluminum foil, wooden sticks, clear transparency sheet, and no material (i.e., the control). He then asked the students to individually predict and record which of these materials would best absorb, reflect, and transmit radiation.

With the exception of Dylan and one of Noelle's answers, all of the student team predictions were based on scientific conceptions. When asked to predict which materials will best absorb radiation, Marie and Noelle wrote "black construction paper," and Sheldon wrote, "the darker ones." These answers are based on the scientific conception that *dark colors absorb radiation/light energy*. However, Noelle also predicted that "aluminum foil" would best absorb radiation, which is also what Dylan wrote. Neither Noelle nor Dylan provided further explanation of this alternative conception, that aluminum foil will absorb radiation. When asked to predict which materials will best reflect radiation, the opposite of absorption, most of the students chose materials that are the opposite of dark colors. Marie wrote, “the white,” while Noelle was more specific with, “the white felt and paper,” and Sheldon chose “the lighter ones.” These answers are based on the scientific conception that *light colors reflect radiation/light energy*. For this answer, Dylan predicted that “black felt” would reflect radiation the best, which is an alternative conception. For the final prediction, which materials best transmit radiation, Marie, Noelle, and Sheldon all wrote about the “clear” materials. Sheldon wrote, “the clear one,” Noelle wrote, “the clear transparency sheet,” and Marie wrote, “the clear wax sheet.” Although wax paper was not an option, later in the lesson Marie clarified to the researcher what she meant. She did not know what “transparency sheet” was, so she assumed it was similar to clear plastic wrap. However, when she wrote her answer, she was thinking “Saran wrap” but accidentally wrote another kitchen material, “wax sheet.” Either way, Marie, Noelle, and Sheldon correctly based their predictions on the scientific conception that *clear materials transmit radiation/light energy*. Similar to her previous two responses, Dylan seemed to have an alternative conception and predicted that “wooden sticks” will best transmit radiation. Although Dylan used scientific conceptions earlier to describe what happens to materials when they absorb and reflect light, she did not apply those conceptions to her predictions about which materials would best absorb, reflect, or transmit light. However, most of the rest of the team did.

After they made predictions, the class did the data collection portion of the radiation lab. Each of the eight materials was taped to the top of a cup and placed directly under a heat lamp. A temperature probe was poked through the side of each cup to measure the air inside the cup, with this temperature acting as an approximate measure of how well each material absorbed, reflected, or transmitted radiation. Each student team in the class was assigned to record the temperature of one or two materials during the experiment. The student team was the to the cup with aluminum foil on top.

During the experiment, the class turned on the heat lamps and then recorded the temperature change of the air inside the cups every 30 seconds for four minutes. During data collection, Noelle read and announced the temperature readings, and the other teammates recorded these data in their engineering notebooks. Marie commented that the team’s material was “sad” since it was not changing much compared to the other materials. She and the researcher then talked.

Researcher: So if it's not heating up very much, does that tell you…do you think aluminum is absorbing it, reflecting it, or transmitting?
Marie: Reflecting, I think. Yeah, it's reflecting.

Here, Marie combined her understanding of absorbing, reflecting, and transmitting radiation with the data being collected to reach the conclusion that the aluminum foil was reflecting the light.

After the data were collected, Mr. Parker asked the student teams to make sure everyone on team had their team's data recorded in their engineering notebooks. Then, he tasked the students with calculating the overall temperature change over the four minutes of data collection. As the student team did these tasks of making sure they all had the same data and calculating their overall temperature change of 7°C, they discussed how their results compared to their expectations.

Marie: I thought it would heat up.
Noelle: Yeah, I thought ours would heat up really well, too. And then the wooden sticks over there was in the 30's.
Researcher: Why did you think it would heat up?
Noelle: Cause it's, it's more…
Sheldon: It's metal.
Marie: Yeah, it's metal.
Noelle: Is it a metal?
Sheldon: I thought it would get way hotter.
Noelle: See, I thought it was a type of metal. Is it a type of metal?
Sheldon: Yeah.
Researcher: Mm-hmm *(affirmative)*
Noelle: So I thought it was going to heat up a lot more than that.
Sheldon: Yeah.
Marie: Yeah.

Earlier in the activity, Noelle and Dylan had listed aluminum foil as a material they predicted would absorb radiation, while Marie and Sheldon had not written a prediction about aluminum foil. However, in this discussion, the team agreed that they all thought that the aluminum foil would heat up, or "get way hotter," because it was a type of metal. Because the previous lesson was about conduction, and the student team learned that metals are good heat conductors (i.e., transfer heat quickly), it seemed that the students based this prediction on an alternative conception that <u>aluminum foil will heat up (in the radiation lab) because it is metal (and thus conducts heat)</u>.

After the teams finished their calculations, Mr. Parker asked them to share their results with the whole class. These results were shown to the students on the Master Data Table, which Mr. Parker wrote on the white board at the front of the class. The class's data are in Table 4.4.

Table 4.4. *Whole class Master Data Table for radiation lab*

Material	Initial temperature (°C)	Final temperature (°C)	Temperature increase (°C)
Control	22	52	30
Transparency sheet	22	67	45
Wood	22	38	16
Aluminum foil	22	29	7
Black paper	22	40	18
White paper	22	40	18
Black felt	22	44	22
White felt	22	51	29

Once the overall temperature change data were collected, Mr. Parker started Lesson 5, which was to analyze the radiation lab data by making graphs of temperature versus time. Using a whole class discussion, he guided the class through making the essential features of a graph, such as title, axes, labels, interval, and scale. After the initial template of the graph was created in their engineering notebooks, Mr. Parker had the student teams plot the data points for their assigned material in the radiation lab. Although the student team worked together to plot the data for the aluminum foil, they had slightly different graphs because all team members except Noelle had at least one inconsistent interval on an axis. However, the general shape, which for aluminum foil was a slight temperature increase over time, was the same for all students on the team.

After the student teams finished graphing their data, Mr. Parker led the students through a series of analysis questions. For each question, he first asked students to record their answer individually in their notebooks, and then he followed with a whole class discussion.

First, Mr. Parker prompted the students to analyze their own team's data with the prompt, "What patterns do you observe in the lines of the graph?" Marie was the only student to notice the overall shape of the graph with her answer of, "The line starts to go up and then starts to even out." Because of the very small temperature increase of the aluminum foil during the radiation lab, it was more difficult to see this trend in the student team's data as compared to other materials, so it makes sense that the other team members did not comment on it. Instead, Dylan, Sheldon, and Noelle focused on the fact that their graph of aluminum foil gradually increased in temperature. Noelle referred to specific values, writing, "They increase by one or two degrees every 0.5 seconds." Sheldon and Dylan's answers were more qualitative, writing, "They are slightly going up," and, "They are not spreaded out a lot from each other," respectively. All four team members' analysis of their graph were correct, though they focused on different aspects.

Mr. Parker then showed the class a graph he made which contained the data for the white felt and black felt. He asked the students to compare the two materials. Dylan and Sheldon commented about both materials together, writing, "They both increase from where they start," and, "They both shoot up really fast," respectively. In contrast, Marie and Noelle wrote about the difference between the two materials, writing, "the white felt is increasing more/much faster than the belt felt." This observation is correct, since the white felt did have a higher temperature increase than the black felt, as seen in Table 4.4. Similar to the previous question, the students' analyses were correct, though they did slightly different analyses of the data.

Finally, Mr. Parker showed the students a graph he made which contained the data for all eight materials and asked questions about which materials best transmitted, absorbed, and reflected light. For the prompt of which material transmitted radiation, Marie and Sheldon answered, "the transparency sheet," which is a correct interpretation of the data and based on the scientific conception that *clear materials transmit radiation/light energy*. However, Noelle answered, "white felt," and Dylan answered, "black paper," neither of which are based on a scientific conception of transmission of light. It is unclear what conceptions or data Noelle and Dylan used when thinking about the answer to this question.

The next series of questions were about absorbing light. When asked whether the white felt or black felt absorbed more radiation, Dylan, Sheldon, and Noelle wrote that the white felt did. (Marie did not answer the question because she was talking to another student on a different team at the time.) Given the whole class data in which the white felt had a higher increase in temperature than the black felt, this analysis was correct. When asked whether the white paper or black paper absorbed more radiation, the student team all answered that they absorbed the same amount of radiation. Again, this is correct analysis of their class's data, given that the temperature increase of both materials was 18°C (see Table 4.4). The last question in this series was, "In general, which absorbs more light, dark or light colored materials?" Marie, Dylan, and Sheldon answered that dark materials absorb more radiation, and Noelle answered "light colored materials." Marie, Dylan, and Sheldon were correct in the sense that their answer is based on the scientific conception that *dark colors absorb radiation/light energy better than light colors*. However, Noelle's answer was also correct given the actual data from the radiation lab, that *light colors absorb more because they had the larger temperature increase in the radiation lab*.

After this series of questions, Mr. Parker led a whole class discussion about this apparent discrepancy between the scientific conception and the data collected. He emphasized that they were actually measuring the temperature of the air inside the cup, not the temperature of the material itself, which may have affected the results. Students proposed various ideas about why the white felt increased more than the black felt. For example, one student from a different team said that maybe the white felt was thin enough that some light went through it rather than being reflected. Mr. Parker ended the discussion by telling the students, “So there could be a lot of other factors that we may not have considered that gave us the results that we did,” and reminding the students that in general, dark colors tend to absorb better than lighter ones.

The final prompt was, “What kinds of materials reflected more light?” All four members of the student team wrote “aluminum foil.” Additionally, Noelle and Sheldon provided a justification for their answer based on the data. Sheldon wrote, “because it’s temp increase was the lowest,” and Noelle wrote, “because it had the lowest temp.” All of these responses were correct interpretations of the data, and they are related to the scientific conception that *metals reflect radiation/light energy*.

In summary, many but not all of the student team’s answers to the analysis questions were based on scientific conceptions. Marie and Sheldon both based their answers about transmitting radiation on a scientific conception, while Noelle and Dylan did not. They had mixed responses about whether dark or light colored materials would best absorb radiation, but this was due in part to a contradiction between the scientific conception and their actual class results. Finally, they all agreed that aluminum foil reflected radiation.

4.2.1.5 Lesson 6: Getting to know the context.

During the final lesson in the learn (about the problem) step of an engineering design process, students learned more about the context of the challenge and reviewed the various heat transfer concepts that were addressed in prior lessons. This was the first opportunity for students to think about convection, conduction, and radiation in the same lesson. Although the student team had demonstrated many scientific conceptions about these processes of heat transfer in earlier lessons, they struggled when required to think about the three methods of heat transfer in combination.

Mr. Parker began Lesson 6 by briefly reviewing temperature, thermal energy, convection, conduction, and radiation. He then asked the students to apply these concepts to the engineering challenge. At one point, Sheldon participated in this whole class discussion.

Mr Parker: What has our client asked us to do to test our cooker containers?
Sheldon: We're gonna have a little model fish, and then we're going to see which one gets the hottest in 10 minutes.

Sheldon correctly identified that one of the criteria of the cooker container was the "get the hottest", or increase the temperature, the most in 10 minutes of testing.

To help students learn more about the model fish, Mr. Parker passed out one model agar fish to each group. The student team had a lively discussion about the agar fish and made several observations, none related to heat transfer. A student from another team asked Mr. Parker if the fish will melt once they are placed in the solar oven. Mr. Parker answered this question for the whole class, telling students that no, the fish will not reach a temperature high enough to melt in the cooker containers. Sheldon then whispered to his teammates, "But they'll be hot," indicating that he anticipated that the fish would have a large temperature increase after testing. Mr. Parker then collected the agar fish from the students.

In addition to learning about the model agar fish, the students needed to learn more information about the solar oven before they began to think about generating solutions for the engineering challenge. Mr. Parker asked students to gather around the classroom solar oven as he explained its features. He also projected a cross-sectional model of the solar oven on the front screen. This model is shown in Figure 4.2.

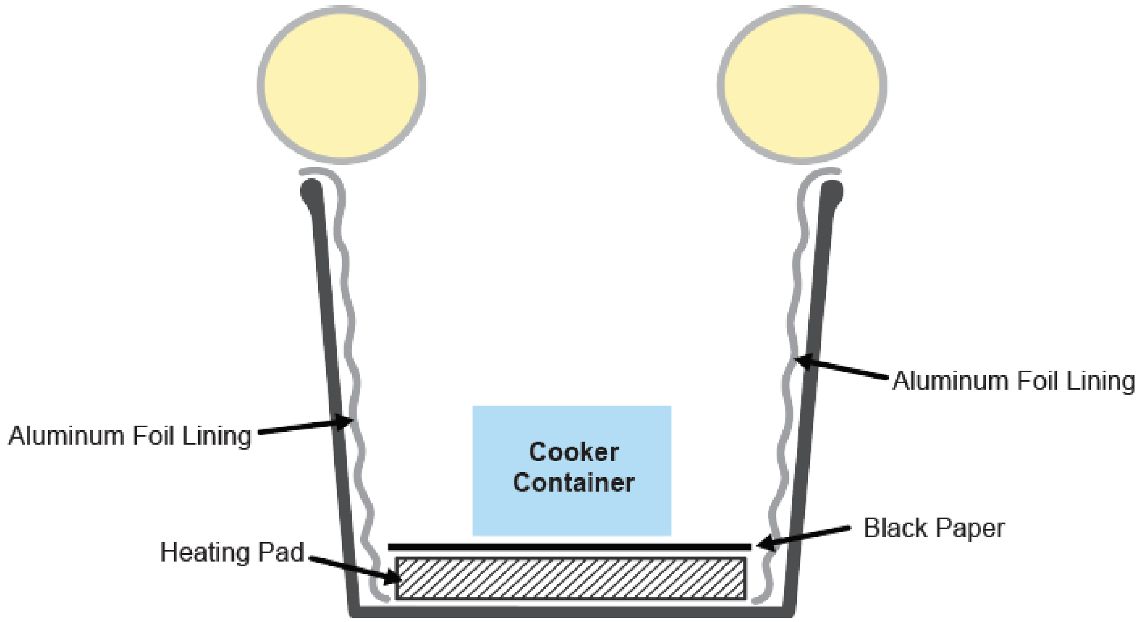

Figure 4.2. Cross-sectional model of the classroom solar oven. Adapted from *Ecuadorian Fishermen: An EngrTEAMS Unit* (p. 88), by K. Berg et al., 2017, West Lafayette, IN: School of Engineering Education, Purdue University. Copyright 2017 by the Purdue Research Foundation. Adapted with permission.

The solar oven was a large plastic tub. There were four heat lamps attached to the top, one on each side, that represented the sun. Mr. Parker also told the students that the heating pad covered by black construction paper at the bottom of the container represented warm coals that the cooker container would be placed on. (See Figure 4.2.) Finally, he pointed out that the four sides of the tub were lined with aluminum foil. Once all students had been able to make observations about the classroom solar oven, Mr. Parker asked them to return to their teams.

Mr. Parker gave students the prompt, “In the classroom solar oven, how would heat be transferred to the cooker container through: 1) convection, 2) conduction, and 3) radiation?” He told students to discuss the prompt in their teams and then write down their responses. The goal of this prompt was for students to identify that: a) radiation would come from the lamps and be reflected off of the aluminum foil sides of the solar oven, and thus they would need to think about how the top and sides of their cooker containers could absorb or transmit radiation; b) the heating pad would be in direct contact with the cooker container so conduction would occur, and thus they would need to think about using conductors on the bottom of their cooker containers; and c) convection would occur as the warm air inside the solar oven rose out of the oven, and thus they would need to design a cooker container that would keep the hot air in the cooker containers.

The student team struggled with this prompt and did not finish. Sheldon started the conversation by asking, “What is convection again?” They started to look through their notebooks, with Marie flipping through various pages and Noelle and Sheldon immediately going to the Vocabulary section. However, although Noelle and Sheldon both found “conduction” and “conductors” in the Vocabulary section, they could not find “convection.” Noelle eventually found the key term in her notebook, reading aloud what she had written, “The process of heat transfer this represents is the process of convection.” The researcher then asked a follow up question.

Researcher:	But what, when they say “this process represents convection,” what are you, what were you talking about with that?
Noelle:	Oh! Like when you touch, so when you touch something cold. So when we did the ice cubes, it would, the heat would transfer to the ice cubes…right?
Marie:	I am blanking on this.

At first, Noelle thought of the ice cube experiment, which was done to illustrate the heat transfer process of conduction. Marie admitted to “blanking on this,” not being able to think of anything nor find anything in her notebook. Marie was not present in class on the day that the students learned about convection, so she did not have anything about convection in her notebook.

The team stopped looking through their notebooks and fell silent. However, Noelle overheard Mr. Parker talking to another group, which prompted her to start another conversation with the team.

Noelle:	When you heat up air, it becomes less dense.
Sheldon:	Yeah.
Noelle:	I was just listening to Mr. Parker.
Sheldon:	Is that for convection?
Marie:	*(reading the prompt)* “So in the classroom solar oven, what would your heat, what would heat be transferred to your cooker container through convection?”
Noelle:	The air would heat up and it would…
Sheldon:	Go through our cooker containers?
Noelle:	…cook it?

The team still seemed unsure, but Sheldon and Dylan starting writing an answer in their engineering notebooks. Noelle proposed skipping convection and moving on to conduction, but Dylan and Sheldon stopped her, saying they already wrote something. Noelle asked what they had written.

Dylan:	“The air would heat up,” is what I put down.

Noelle: Oh, for convection, you put the air would heat up or something?
Dylan: Yeah.
Sheldon: Yeah. Cause that's what you said. I wrote, "The air will heat up and heat up the cooker container."

Marie and Noelle started to write an answer for convection in their notebooks, but Noelle suddenly remembered the concept.

Noelle: Oh! It circulates! *(Noelle makes a circular motion with her hand.)* The hot air rises and then, the cold air comes down and then heats up and then the hot air rises.
Marie: So like boiling water?
Noelle: So it's just like a *(makes repeated circle motion with hands)*.

Noelle remember the scientific conception that *hot fluids rise and circulate in convection,* which prompted Marie to relate the situation to one she had encountered in her everyday life, boiling water. At this point, both students wrote a response in their notebooks. Marie wrote, "The air would heat up and rise and the cold air would go down and then heat up," and Noelle wrote, "The air would heat up and rise and the cold air will come down and heat up." All four team members related convection to air heating up in the solar oven, and Marie and Noelle also used the scientific conception that *hot fluids rise and circulate in convection*.

The student team had just begun to talk about "conduction" when Mr. Parker stopped the small group portion of the activity. In the time it took the student team to determine a definition of "convection," most of the other teams in the class finished the activity. Thus, Mr. Parker moved on to a whole discussion about the prompt. During the discussion about convection, Mr. Parker asked, "Now that warm air will probably, since there's no top to our solar oven, it might just pass up and out, right?" A student proposed making a lid to keep the air inside the container. Noelle then added, "So you can build a lid and the air won't rise" to her notebook response about convection in the solar oven, which is a reasonable application of the scientific conception that *hot fluids rise* to the design of a cooker container.

The whole class discussion then turned to conduction, and Mr. Parker called on Noelle.

Mr. Parker: Noelle, what do you think? So where's conduction taking place, so that your fish conducts thermal energy?
Noelle: Um…
Mr. Parker: So again, our conduction lab was, we modeled with the ice cube, right, and we learned and we identified that conduction is the transfer of heat from that block. And we noticed that metals worked best of conducting

heat, right? And it passed it up to the ice cube that was resting on the top. So where's conduction taking place in this?

Noelle: The heating pad?

Mr. Parker: So from, yeah, the cooker container setting right on top of this. So it's directly conducting heat from the heating pad through the black paper directly to the bottom of your cooker container.

After Noelle correctly identified that the heating pad would be the source of conduction to the cooker container, she wrote, “The coals will pass heat off to the cold fish,” in her notebook. This seemed to be based on the scientific conception that *conduction is the transfer of heat through a solid or from a solid to another solid, liquid, or gas*.

During the whole class discussion about how radiation was occurring in the solar oven, Marie added “the light waves,” to her engineering notebook, and Noelle wrote, “The lights radiate heat off to the fish.” These answers are related to the scientific conception that *radiation is the transfer of heat across space in the form of light waves.* During this activity, Noelle correctly identified how all three methods of heat transfer were related to the solar oven, Marie identified two (convection and radiation), and Sheldon and Dylan only had some limited information about “air heating up” for convection in their notebooks.

Mr. Parker then prompted the students to individually answer the prompt, “Which of these processes of heat transfer do you think you will need to most carefully consider when you design your cooker container?” Marie and Sheldon both answered “radiation” and also provided a justification for their choice. Sheldon wrote, “because the sun produces radiation,” and Marie similarly wrote, “because if there’s no sun then there is not going to be any fish to cook.” Noelle wrote, “conduction,” but did not include a justification. Dylan did not answer the question. Given the set-up of the solar oven, either radiation or conduction would be reasonable answers to the question; thus, three of the four students provided a reasonable response.

After the agar fish and solar oven exploration activities, Mr. Parker moved on to the part of Lesson 6 that included two concept review activities. For the first review activity, he chose to use the online program *Quizziz* (https://quizziz.com), which he used before in his science class so students were familiar with it. In the program, students individually answered multiple choice questions, and their final scores depended on how many correct answers they chose and also how quickly they completed the quiz. The questions provided a situation or definition and then asked students to determine if they were best described by conduction, convection, or radiation. For example, one prompt was, “Heat we feel from the sun,” with the correct answer being “radiation.”

During the *Quizziz* review activity, Sheldon and Marie rushed to complete it as quickly as possible, and they were some of the first students to finish. Dylan and Noelle took more time to finish. The students were already aware that, in addition to correct answers, time to answer was also a criterion in their class ranking. Of the 16 questions, Noelle answered 11 correctly, which means she was ranked 5th in the class (out of 21 students). However, the other three students on the team struggled when compared to their classmates. Dylan answered 8 questions correctly (17th in class), Marie had 7 correct answers (18th in class), and Sheldon only answered 6 questions correctly (20th in class). As a team, they averaged 46% correct on questions to which the answer was conduction, 50% correct on questions about convection, and 55% on questions about radiation. The amount of time they spent likely contributed to their scores, since Noelle vastly outperformed Marie and Sheldon. In sum, the student team did not do well on the processes of heat transfer review quiz, both in terms of absolute scores and when compared to other students in the class.

The second concept review activity was a notebook prompt that students answered individually. The prompt was, “Describe the similarities and differences among the three processes of heat transfer: conduction, convection, and radiation.” The student responses are in Table 4.5.

Table 4.5. *Students' notebook entries responding to the prompt "Describe the similarities and differences among the three processes of heat transfer: conduction, convection, and radiation?"*

Student	Notebook entry
Marie	The similarities between conduction, convection, and radiation is that they all transfer light in some way. The differences is that they all have different ways of transferring the light. Radiation is through sunlight, conduction is through how thermal energy, convection is through how the air transfers through liquids.
Sheldon	They each produce heat. They each produce heat in a different way.
Noelle	They all give heat and warms something up. Conduction is when you touch something that doesn't have the same temperature as you so you pass heat off but convection is where the warm air rises and the cold air sinks and lastly radiation is when something gives off light and heats something up.
Dylan	The similarities is that they all do something with heat. Conduction is how heat energy transfers, radiation is that dark colors absorb heat.

As shown in Table 4.5, the student team used a few scientific conceptions about heat transfer, but most of their conceptions were partially or fully incorrect.

For the similarities, Sheldon, Noelle, and Dylan all wrote something about "heat." Dylan's answer, "that they all have something to do with heat," was correct but redundant given the prompt. Sheldon and Noelle were more specific, stating that the processes "produce" and "give" heat, respectively. Marie was the only team member to use the verb "transfer," but her statement that "<u>they all transfer light in some way</u>" was an alternative conception.

For the differences, Sheldon's response that they act "in a different way" was true, but he was the only team member to not specifically attempt to describe conduction, convection, or radiation. Of the three processes of heat transfer, the remaining team members had the most scientific conceptions about radiation. Noelle and Marie both referred to "light." Marie's answer of "sunlight" was one specific source of radiation, and Noelle's answer was close to the scientific conception that *radiation is the transfer of heat across space in the form of light waves*. Dylan focused on a specific effect of radiation, that "dark colors absorb heat," which is fairly close to the scientific conception that *dark colors absorb radiation/light energy*. For conduction, Noelle's statement about "pass[ing] heat off" when you touch something is based on the scientific conception that *materials at the same temperature can feel different because they transfer heat at* *different rates*; this response is one example of conduction. In contrast, Dylan's response that "conduction is how heat energy transfers" is overly broad, since all three processes are how heat energy transfers. Marie's comment that "conduction is through how thermal energy" is too incomplete to determine an underlying conception. For convection, both Marie and Noelle wrote that it is related to air. Noelle's comment that "warm air rises and the cold air sinks" is based on the scientific conception that *hot fluids rise and circulate in convection*. However, Marie's comment that "convection is through how the air transfers through liquids" seems to be unrelated to temperature or heat.

In the whole class discussion following this writing review activity, the student team participated frequently and well. When Mr. Parker asked why an ice cube feels cold to humans, Marie said, "The heat from your hand goes to the ice cube so it feels cold." This statement is based on the scientific conceptions that *materials at the same temperature can feel different because they transfer heat at different rates* and *the direction of heat transfer is from hotter objects (i.e., objects with higher temperatures) to colder objects (i.e., objects with lower temperatures)*. When Mr. Parker asked about radiation, Marie said, "sunlight." Mr. Parker clarified, "Okay, light, so all different forms of light. But in our case, for our engineering design, it's going to involve sunlight." Finally, when Mr. Parker reviewed conduction, he asked what are the best types of conductors, and Sheldon said, "Metals." This idea part of the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. Although their written responses showed a mix of conceptions, Marie and Sheldon's participation in the following whole class discussion demonstrated several scientific conceptions.

4.2.2 Solution Generation Part 1: Initial Design

The first solution generation stage of the *Ecuadorian Fishermen* curricular unit was comprised of four steps of an engineering design process: plan (a solution), try (the plan of the solution), test (the solution), and decide (about whether the solution is successful). Lessons 7 and 8, which is when the students did the planning step, were implemented in a little less than four full class periods. In Lesson 9, students tried their plan, which meant they built their prototype, in one and a half class periods. Mr. Parker implemented Lesson 10, in which students tested and decided about their initial design, in a little over one full class period. Overall, the implementation of the initial solution generation stage took approximately seven class periods.

4.2.2.1 Lesson 7: Exploring materials and Planning: Idea generation and Lesson 8: Planning: Idea selection and Evidence-based reasoning.

Lessons 7 and 8 are distinct lessons in the *Ecuadorian Fishermen* curricular unit, but they are both within the plan (a solution) step of an engineering design process. Therefore, they are described together in this section. In Lesson 7, student teams were given a set of materials that they would be able to use for their design challenge, and they discussed how these materials would transfer heat. Then, students were tasked with individually generating at least three ideas for cooker container designs; these ideas needed to include sketches and justifications. At the beginning of Lesson 8, individual students evaluated the pros and cons of their design ideas before meeting as teams to select one idea. Next, each student team filled out an evidence-based reasoning graphic that reviewed the problem including criteria and constraints, simplifying assumption, their design idea, data/evidence to support the idea, and a justification of the idea. Finally, each student reflected on why their team chose their design solution. During these two lessons, the student team used a variety of scientific and alternative conceptions as they attempted to apply their knowledge about the three processes of heat transfer while designing a cooker container solution to the engineering challenge.

In the first activity of Lesson 7, the student team discussed the heat transfer properties of the 11 materials that they could use to create their prototype: aluminum foil, copper wire, steel washers, paper clips, pipe cleaners, white and black construction paper, white and black felt, craft sticks, and transparency sheets. They were given one of each material and the prompts:

1. Which materials will best transfer heat via conduction (i.e., are conductors)? Why do you think so?
2. Which materials will best block heat transfer via conduction (i.e., are insulators)? Why do you think so?
3. Which materials will best absorb radiation? Why do you think so?
4. Which materials will best reflect radiation? Why do you think so?
5. Which materials will best transmit radiation? Why do you think so?

However, the student team became very confused during the discussion, and they were not able to complete the activity in the time it took the other teams to do so.

The student team initially used scientific conceptions when attempting answer the first prompt and identify which materials are conductors. Sheldon picked up and felt each of the metal materials: the aluminum foil, paper clip, metal washer, and copper wire.

Sheldon: This [steel washer] is probably coldest.

(Marie also felt the steel washer and commented on how it felt.)

Marie: So…metal?
Sheldon: So, what's this called?
Marie: A washer.
Noelle: It's a washer.
Sheldon: So, yeah, metal.
Noelle: So, copper wire, or the washer…
Marie: I think the washer.
Noelle: Just one of them?
Sheldon: So let's put "metals."
Marie: Well…
Sheldon: Cause this one [paper clip] is also cold.

At first, the student discussed only metals as conductors, which is part of the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. The discussion they had was whether they should choose a specific metal to record in their notebooks, or whether they should just write "metals." To determine which material was the best conductor, the team used a heuristic that *a material that feels colder will transfer heat faster (i.e., is a better conductor)*, which is based on the scientific conception from Lesson 3 that *materials at the same temperature can feel different because they transfer heat at different rates*. In other words, the team created a heuristic for determining conductivity by combining the conceptions that *how a material feels is related to the rate of heat transfer* and *conductors are materials that transfer heat quickly*.

After this excerpt, Marie and Noelle began to discuss the structure of the metals, pointing out the shapes of the metal objects and asking the researcher if they would be able to use sheets of the different metals instead of the shapes given to them. The researcher responded that they needed to use the materials as given to them. They then started to talk about using a wire or pipe cleaner to lock the lid of the container to its bottom. Meanwhile, because none of the team members had written an answer for the first prompt, Sheldon twice tried to re-focus the team's attention on the prompts, saying, "Let's just put metals!" However, Marie and Noelle ignored him.

Marie then looked at a data table from the radiation lab in Lessons 4 and 5, which Mr. Parker had left written on the front white board of the classroom. However, the data table on the white board contained a different class's data, which had mostly similar results to the student team's class but two major differences when compared to the data in Table 4.4. The data on the front white board showed that the cup with white felt increased to 69°C, and in the student team's class the white felt cup had increased to 51°C. Additionally, in the other class's data, the white felt had the largest temperature increase of all eight materials tested, but in the student team's class the transparency sheet had the largest temperature increase in the radiation lab.

After Marie looked at the radiation lab data table on the front white board, she said, "I'm so confused. Wait, this one [white felt] would be great for number 1 because it had 69 from the test, right?" Although Marie was correct that the white felt had a large temperature increase in the radiation lab, she did not realize that she was using data from a radiation lab to answer prompt 1, which asked about conductors. None of the other members of the student team realized this either, as is evident in the following discussion.

Noelle: *(reading the first prompt)* "Question 1: Which materials will best transfer heat via conductor?"
Marie: The white felt?
Noelle: The white felt because it had the highest, it has the highest temperature.

All four team members then wrote, "white felt" as their answer for the first prompt. Additionally, Marie, Sheldon, and Noelle wrote, "because it has the highest temperature" as the justification for their answer. Because no one on the team saw a problem with using the radiation lab data to answer a question about conduction, the team essentially created an alternative conception that <u>white felt is a good conductor because it had the highest temperature increase (during the radiation lab)</u>. This was the first of many alternative conceptions the team had during the initial solution generation process, and most of these alternative conceptions were created as the student team combined various ideas and vocabulary about conduction and radiation to create one set of rules about how well materials transfer heat.

The student team discussed the second prompt, "Which materials will best block heat transfer via conduction (i.e., are insulators)? Why do you think so?" Sheldon looked at the radiation lab data table on the front white board before starting the discussion.

Sheldon: Aluminum foil might be a good insulation because it kept it the coolest. Because that means it didn't really like *(brings his flat palm to aluminum foil and gently hits it a few times)*. The cup air was the same, so that means it's a good for insulation.
Noelle: Um, do you guys think for the insulator, aluminum foil-
(Noelle was interrupted by an unrelated humorous discussion)
Marie: I think aluminum file, aluminum foil would be best because it has lowest temperature out of all of them. So it would block the heat.
Noelle: Well, you wouldn't want to block the heat [in the container].
Marie: It says, "Which materials will best block the heat transfer via conduction?"

Noelle: Oh, sorry. The aluminum foil. Wait, is the insulator to keep the heat in?
Sheldon: Yeah. Once you get this heat in, this [aluminum foil] will keep the heat in.

Similar to the logic used to answer the first prompt, here the team used the radiation lab data to answer the question about insulators. They created another alternative conception that <u>aluminum foil is a good insulator because it had the lowest temperature increase (during the radiation lab)</u> by combining ideas from conduction and radiation.

The researcher noticed that the student team was confusing various concepts within conduction and radiation. In an effort to help the team, she asked them, “So maybe it would help if you read through all five questions. So what are the five different kinds of material properties?”

Noelle: I think that [aluminum foil] will be best to reflect radiation.
Marie: I think block because it had the least amount of temperature change.
Sheldon: Well, it does reflect the light!
Marie: And it reflects light. I don’t know.
Sheldon: So yeah, it might reflect radiation.
Noelle: I think that [aluminum foil] could be radiation block.
Sheldon: Yeah, cause it’s reflecting light back at me.
Noelle: I think the black construction paper would be…
Marie: No because this [black paper] absorbs light. We’re trying to block light.
Sheldon: I’m thinking this [black felt].
Marie: I’m thinking this [aluminum foil].
Sheldon: No, this [white felt] because insulation is always a light color.
Marie: No, this one [white felt] would be heat, because that one would be. That would be number one because the white felt had the highest, the most temperature.

In this conversation, Marie, Sheldon, and Noelle used a variety of scientific and alternative conceptions about thermal properties of materials. One of the scientific conceptions used was that *dark colors absorb radiation/light energy*; Marie used this when she said, “this [black paper] absorbs light.” Additionally, the three students agreed that aluminum foil reflects radiation/light, which is an extension of the scientific conception that *metals reflect radiation/light energy*. However, Marie still thought that it will “block because it had the least amount of temperature change;” here, she appears to be using the word “block” in terms of the prompt, “Which materials will best block heat transfer via conduction (i.e., are insulators)?” In other words, Marie’s alternative conception was that <u>aluminum foil is a good insulator because it had the lowest temperature increase (during the radiation lab)</u>. Based on her final statement, she also thought that <u>white felt is a good conductor because it had the highest temperature increase (during the radiation</u>

lab). In contrast, Sheldon proposed writing "white felt" as an insulator "because insulation is always a light color." Here, he was not basing his statement on a scientific conception but rather on his previous experience with insulation material in his everyday life.

This conversation demonstrates two other areas of confusion. First, it is not clear that the members of the student team always knew which prompt they were discussing. Over the duration of the conversation, they discussed several materials properties related to heat transfer, frequently switching between them. Second, it seems as though the team thought that a material could only be used as an answer to one of the five prompts. A portion of their conversation was debating whether aluminum foil should be listed as a material that reflects light or blocks heat transfer via conduction (i.e., are insulators); they did not realize they could use it for both questions.

Seeing that the team was still confused, the researcher again intervened.

Researcher: So what's the difference between conduction and radiation?
Marie: Radiation has, it has light.
Noelle: Conduction means…
Sheldon: Radiation is light.
Marie: And conduction is how heat transfers-
Noelle: How heat energy transfers…
Marie: -through a solid.

Marie, Noelle, and Sheldon expressed short versions of two scientific conceptions about radiation, that *radiation is the transfer of heat across space in the form of light waves*, and conduction, that *conduction is the transfer of heat energy through a solid*. The researcher then asked them which labs they did for conduction and which for radiation, and the team struggled to remember.

Because the clarifying questions and prompts said to the student team had not lessened their confusion, the researcher explicitly gave the students a hint about the prompts.

Researcher: So, just a reminder, the first two questions are about conduction, and the last three are about radiation.
(Dylan asks which question the team is on; Noelle helps her.)
Sheldon: So that means we can use this [aluminum foil] twice, once for radiation and once for conduction?
Noelle: Wait, this one [white paper] would be a conductor.
Researcher: *(to Sheldon)* Yeah, what do you mean by that? So in conduction, would that [aluminum foil] conduct or insulate heat?
Sheldon: This [aluminum foil] would insulate in conduction.
Researcher: So think about the ice cube.
Noelle: It melt, it kept it a solid longer.
Marie: I still think this [aluminum foil] would block out heat.
Sheldon: Yeah.

Marie:	It would block out heat because it has the lowest temperature.
Noelle:	But it is, it's, it makes things a solid longer, so that means it's cold. It can get really cold.
Sheldon:	So that means it's an insulator.

Although Sheldon now understood that they could list materials twice, once for radiation and once for conduction, it unclear whether the rest of the team did. Also, when asked about the conduction properties of aluminum foil, Sheldon, Noelle, and Marie all thought it would be an insulator or "block out heat." Marie was still using the radiation lab data to determine what would "block out heat," which gave the alternative conception that <u>aluminum foil is a good insulator because it had the lowest temperature increase (during the radiation lab)</u>. Sheldon and Noelle seemed to justify their idea that <u>aluminum foil is a good insulator</u> because of the ice cube conduction lab results. Sheldon was correct in remembering that *when a material keeps an ice cube solid for a longer time, that material is an insulator*; however, Noelle was not correct when she said that aluminum foil (a metal) kept "things [ice cubes] solid longer." Finally, it is unclear what data or experiences Noelle thought about when she asserted, "<u>this one [white paper] would be a conductor</u>," but that is also an alternative conception about the conductive properties of paper.

At this time, most of the other teams in class had completed all five prompts, so Mr. Parker asked the groups to return their materials and turn to face the front of the room for a whole class discussion. As Sheldon left to return the materials, Noelle and Marie continued to argue about the aluminum foil and whether it would block out heat through radiation or via conduction. Noelle continued to justify her idea with her incorrect memory of the conduction lab, which was that the ice melted faster on metals than wood. When Sheldon returned to the table, he and Marie convinced Noelle that she was remembering the lab incorrectly. The conversation ended with Marie saying, "Exactly! The wood blocked out the heat. I was right!" This was a scientific conception, that *wood is an insulator*, and it was the first time that wood had been mentioned during the small group discussion about the thermal properties of materials. However, the team was not able to continue a conversation about wood because Mr. Parker moved on to the whole class discussion.

During the whole class discussion, most of the teams provided answers to the prompts that were based on scientific conceptions, though there was still some confusion about whether white materials are better at absorbing radiation because of the results of the radiation lab. At one point during the whole class review, Mr. Parker called on the student team.

Mr. Parker:	Alright, let's see, this group up here. What materials do you think will reflect the most radiation?
	(Student team is silent)
Mr. Parker:	Noelle, do you want to… A material that you think will reflect radiation.
Noelle:	Um…
Mr. Parker:	Did your group talk about that?
Noelle:	No, we didn't get to that one.
Mr. Parker:	No, you didn't get there?
Noelle:	Um, aluminum foil?
Mr. Parker:	Okay, why do you think aluminum foil?
	(Student team is silent)
Noelle:	Because it's *(makes a ricocheting, v-like motion with her hand)*
Mr. Parker:	Well let's take a look at our data here. Was there a large temperature change with the aluminum foil in the radiation lab? No? So that means most of that incoming radiation was probably reflected right off of the surface.

Although she seemed unsure, Noelle's answer that aluminum foil would reflect radiation was correct and based on the scientific conception that *metals reflect radiation/light energy*.

During the whole class discussion, Noelle continued to write answers to the five prompts in her engineering notebook. When the class discussed metals being good conductors, she changed her answer to the first prompt from "white felt" to "aluminum foil." The class discussed black felt as a good insulator and good at absorbing radiation, so Noelle wrote "black felt" for the second and third prompts. She added "aluminum foil" to the prompt about materials that reflect radiation and "transparency" to the prompt about materials that transmit radiation. Although her answers for all five prompts were now correct with regards to the thermal properties of materials, it is not clear whether she understood why these materials were listed for each prompt or whether she just copied the answers that Mr. Parker approved during the whole class discussion. None of the other team members added additional information to the prompts during the whole class discussion, so Dylan, Marie, and Sheldon had no materials listed for prompts two through five.

Before the second activity of Lesson 7, students were given a Materials Cost List that contained a list of materials that could be used for their cooker container prototypes, the size of each material (e.g., "1 piece of aluminum foil, 6"x6"), and how much one piece of each material would cost. Given this price information, as well as what they knew about the engineering challenge and their conceptions about heat transfer, Mr. Parker asked them to each come up with three design ideas. The template for each design idea plan included room for three sketches – bottom view, top view, side view – and also a justification section. After completing their three ideas, the students were asked to respond to the prompt, “What are the pros and cons of each of your own solutions ideas?” This activity of individually generating and evaluating cooker container design ideas was done to prepare students to select a single design idea as a team.

This second activity of Lesson 7 took one full class period to implement. During the implementation, there were no whole class or small group discussions; instead, students worked alone on their design ideas. As students worked, Mr. Parker and the researcher talked to individual students and asked them to clarify the design ideas they had written in their engineering notebooks. The students’ written design sketches and justifications, written pros and cons analysis of their design ideas, and spoken interactions with Mr. Parker and the researcher were all used to analyze their design ideas and underlying scientific conceptions. The following results are presented for each student on the team.

Marie completed three design ideas for a prototype cooker container, including sketches and justifications. Some of her design components were based on scientific conceptions, and all of her justifications were correct based on radiation conceptions and radiation lab data. However, she sometimes incorrectly applied a conception, and she also did not consider conduction at all, which led to some unscientific design components.

The top view of Marie’s first design idea is shown in Figure 4.3. It had an aluminum foil bottom and sides, along with a transparency sheet top. Additionally, a piece of black felt was placed on the bottom inside the container.

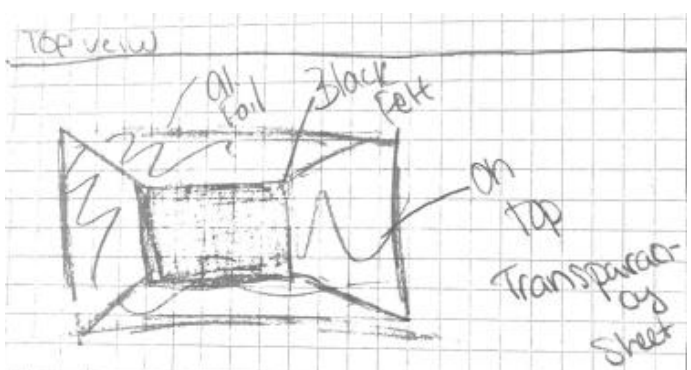

Figure 4.3. The Top View sketch of Marie’s first idea for a cooker container prototype.

For this design idea, she justified her choices of black felt and transparency sheet in writing and when speaking with the researcher. In the Justification section of this idea, she wrote, “Black felt

– it absorbs a bunch of light," and "Transparency sheet – because of how much it heats up to." She also wrote, "it has a lot of light absorbing in it," as the pro of the design idea. Additionally, when the researcher asked her to explain the design idea, she said, "Cause the black felt absorbs light, and then, when the transparency sheet gets hot, it had the highest, well not the highest, but still had high temperature." Here, Marie was referring to the radiation lab data on the front white board that showed the largest temperature increase was the white felt, and the second largest was the transparency sheet. Marie's statement about black felt was based on the scientific conception that *dark colors absorb radiation/light energy*. Although she did not say or write anything about the transparency sheet transmitting light, she did correctly apply a result from the radiation lab that *the transparency sheet had large temperature increase in the radiation lab*. For the aluminum foil component, she wrote, "Al foil – It reflects a lot of light." This statement is based on the scientific conception that *metals reflect radiation/light energy*. However, it is unclear whether she was thinking about the aluminum foil reflecting light inside the container or the outside aluminum foil reflecting light away from the container. Her con of this idea, "The Al foil might not work," does not clarify which of these ideas she meant.

Marie's second design for a cooker container prototype was a wood bottom and sides, all lined with black felt; this container had an open top. In her written justification and twice during a conversation with the researcher, she justified her choice of wood because it would "make it sturdy." For her con of this design idea, she wrote, "the wood might break." Marie was clearly concerned with the sturdiness of the design, which was a relevant concern. However, given that wood is an insulator and reflects radiation, wood was a poor choice to have on the sides and bottom of the container. There was no evidence that she gave any consideration to these thermal properties of wood. Lining the inside sides and bottom with black felt was based on a scientific conception, though, that *dark colors absorb radiation/light energy*. Marie was aware of this, justifying her design by saying that, "Black felt – it absorbs light."

Marie's third design idea had black felt sides and bottom with a transparency sheet top. She only wrote, "Black felt – light," and, "Transparency – the temp," for her justifications, probably because she had written more thorough justifications about black felt and transparency sheet for design ideas 1 and 2. It can be inferred that these brief statements were shortened versions of her previous ideas and scientific conceptions, that *dark colors absorb radiation/light energy* and *the transparency sheet had large temperature increase in the radiation lab*. In her pros and cons, she wrote, “pro – the black felt is a good source of light,” and “con – the transparency sheet might not do its job.” Although black felt is not a “source” of light, her previous statements about black felt indicate that she likely meant something about absorption with this statement. The second statement about the transparency sheet is too vague to provide further evidence of her scientific understandings and ability to apply them to the design challenge.

A final note about Marie’s three design ideas is that she did not take into account conduction from the heating pad at the bottom of the solar oven. Although her first idea included an aluminum foil bottom, this was lined with black felt, an insulator. Similarly, the bottom materials of her second and third ideas were also insulators, wood sticks and black felt, respectively. She also did not include any vocabulary related to conduction in her justifications or pros and cons analysis. It is unclear whether she ignored conduction because she thought it was not worth considering when compared to the effects of radiation, or whether she ignored it because she forgot about it or did not understand it.

Similar to Marie, Sheldon completed three design ideas for a prototype cooker container, including sketches and justifications. Also similar was that he had a mix of scientifically-based and nonscientific ideas for design components. One difference between Marie and Sheldon was that for two of his designs, Sheldon considered both conduction and radiation

Sheldon’s first design was the most complicated yet least scientifically sound of his three ideas. The main body of the container, including the top, bottom, and sides, was aluminum foil. The top foil lid was held on with copper wire hinges and a paper clip latch. On the bottom of the container, Sheldon drew four foldable legs elevating the container; these legs were to be made of wood craft sticks and foldable due to copper wire springs. His justification for the first design was, “I chose foil, because it is a metal.” In an attempt to clarify his justification, the researcher asked him about the pros and cons of this design.

Researcher: Okay, so what’s something you really think is good about that design?
Sheldon: Aluminum foil.
Researcher: Because you have the foil. Okay, why is that good?
Sheldon: Because it would be sturdy.
Researcher: Okay. And what’s, maybe, a con? What’s something that might not work about that?
Sheldon: The legs.
Researcher: The legs? Why not?
Sheldon: They, they might not be able to hold it up.

After this discussion, he wrote, “A pro is, it is made of foil so it is sturdy. A con is, the foldable legs may not work.” Sheldon did not justify any parts of this design idea with conceptions about heat transfer, which could explain why none of the parts are based on scientific conceptions. By elevating the container away from the heating pad at the bottom of the solar oven, there would not be conduction from the heating pad to the cooker container. The container would also not experience much heat transfer from radiation because the top and sides were all made from aluminum foil, a metal that would reflect the radiation away from the container.

In contrast, Sheldon’s second and third design ideas had components that were based on scientific conceptions about heat transfer. Sheldon’s second design is shown in Figure 4.4.

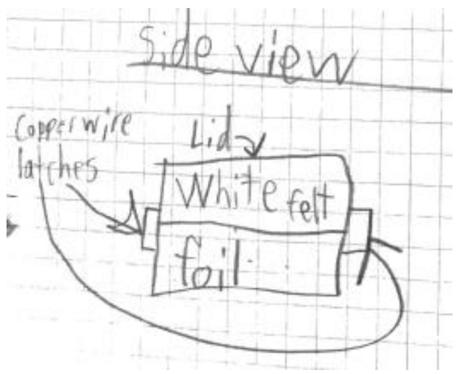

Figure 4.4. The Side View sketch of Sheldon’s second idea for a cooker container prototype.

At first, Sheldon’s side view drawing had “foil” on the top portion and “white felt” on the bottom. The researcher asked Sheldon about this.

Researcher: So in this design, the white felt is on the bottom, and the foil is on top? Is that what your, is that what that means?
Sheldon: I think I put it backwards.
Researcher: Okay. Cause from the top, what’s coming down from the top?
Sheldon: The radiation.
Researcher: The radiation. And from the bottom, what are you thinking about?
Sheldon: The heat conduction.
(Sheldon erases the two labels and switches them.)

Sheldon justified his choice of white felt on top by writing, “I chose white felt because it attracts more radiation than the other materials.” This statement was based on the fact that *the white felt had the largest temperature increase in the radiation lab*. He was concerned about the sturdiness of the white felt, however, writing that “it won’t be sturdy” as the con of his second design idea.

He justified the choice of aluminum foil as the pro of this design, writing, “the bottom is made of foil to help conduction.” Here, Sheldon based this idea on the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. In sum, the two main components of Sheldon’s second design idea, a white felt top and aluminum foil bottom, seemed to be based on data collected in class and a correct scientific conception.

Sheldon’s third design idea was almost identical to the second idea shown in Figure 4.4; the only difference was that he used a transparency sheet on top instead of white felt. He justified this choice by writing, “I chose the transparency sheet, because the radiation will also reach the foil and heat it up faster.” Although he did not explicitly use the term “transmit,” it was implied based on his description of how the radiation “will also reach the foil.” This statement is based on the scientific conception that *clear materials transmit radiation/light energy*. However, this statement that radiation would “heat [the aluminum foil] up faster,” seems to imply that Sheldon thought the aluminum foil absorbs radiation/light energy, not reflect it.

There are a few design features to note about all three of Sheldon’s design ideas. First, all three included a lid and latches, though Sheldon did not explain why he included these components. Also, Sheldon wrote a pro and con about all three ideas, writing, “A pro is they look like they will work. A con is they don’t look professional.” Sheldon thought that all three ideas would be able to cook the fish, even though he only provided justifications related to thermal properties of materials for the latter two design ideas. Also, he noted that they “don’t look professional,” which was not given as a criterion or constraint.

Unlike Marie and Sheldon, Noelle completed only one design idea during the time provided. She initially wrote only “metal” for the bottom of the cooker container, but when asked by the researcher which kind of metal she would use, she chose “aluminum foil.” Although she did not provide a justification for her choice of aluminum foil in Lesson 7, she said, “you could have aluminum foil since it’s good at conducting,” when she described her design to her teammates in Lesson 8. Therefore, she chose aluminum foil for the bottom of the cooker container based on the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. However, Noelle was concerned that by itself, aluminum foil would not be sufficiently sturdy.

Noelle: So down here, I put aluminum foil too. But how will it hold since it's not a very sturdy material. How will it stand and everything?
Researcher: Well, that would be something else for you to think about. So what other materials do you have that might help you?
Noelle: Well, I was thinking, the wooden sticks, wood absorbs well. And so I was thinking maybe tape the wooden sticks and stick them upright.

After this discussion, Noelle wrote that the bottom of the container would be, "lined with wooden sticks," and she also made the sides entirely out of wooden sticks. This idea to put wooden sticks on the bottom and sides of the cooker container prototype was similar to Marie's second idea, since both students wanted to make their designs sturdy. However, while Marie did not provide any information about wood's thermal properties, Noelle said, "wood absorbs well," which is an alternative conception. During the radiation lab in Lessons 4 and 5, wood had the second-lowest temperature increase (see Table 4.4), which means that it mostly reflected radiation. However, because the student team's material of aluminum had the lowest temperature increase during the radiation lab, it is possible that Noelle considered all other materials to be better at absorbing radiation; in other words, wood absorbs radiation/light energy because it did not have the absolute lowest temperature increase during the radiation lab. The final major component of Noelle's cooker container design was the top, for which she had initially written "solar panels" but then changed to "white felt." She did not write a justification for this material choice.

Noelle had another unique design feature in her design idea. She placed a transparency sheet window in one side of the cooker container. Although she did not explain why during this lesson, she later told her teammates that the window was to be able to check on the fish. In other words, the transparency sheet window was not there to transfer heat by transmitting radiation.

During the pros and cons analysis, Noelle wrote statements that were about the entire design rather than any specific component. She wrote two pros, "It will stand," and, "It will hold the fish." She also wrote four cons. "It won't withstand weather," was related to a concern that the cooker container might not be tsunami-proof. Noelle was also the only team member to think about cost, writing, "It will be too expensive." Her list of cons included two related to heat transfer, "It might not warm up," and "It won't absorb light." However, because neither of these statements are about a specific component of the cooker container, but rather the design idea as a whole, it is difficult to interpret what material or materials she was thinking about.

The fourth member of the student team, Dylan, struggled to come up with design ideas. Dylan spent the first 12 minutes of class copying the worksheet templates for the three design ideas, including the "Bottom View," "Top View," "Side View," and "Justification" sections on each template. After copying these prompts in her engineering notebook, she put her pencil down for an extended period of time.

Noticing that Dylan had disengaged, the researcher initiated two conversations with her to help her with the first design idea. Each conversation took approximately three minutes. Most of the talking and asking questions was done by the researcher, and most of Dylan's responses were, "Yes," "No," "Um…," or "I don't know." Therefore, rather than include the full transcripts, overviews of the conversations are provided here with important quotes from Dylan included.

The researcher started by asking Dylan if she had any ideas, to which she said, "No." The researcher then chose to attempt to help Dylan get back on track by decomposing the problem for her. Thus, the researcher asked her about the challenge and what the cooker container needed to do. Dylan flipped through her notebook, thought, then answered, "Increase temperature…like how hot it is inside, so to cook it, right?" The researcher affirmed her answer and then moved on to reviewing the solar oven, asking Dylan what she remembered about it. She said, "I don't know what to call them. Isn't it the heat thing, to put the heat down?" The researcher responded that yes, there are lamps shining light down on the container, using her hands to mimic light shining down on top of the container. The researcher then asked, "So what would you want the top of your container to be to help cook the fish and get all that light?" Dylan responded, "I feel like aluminum foil would get hot enough to do that." Here, Dylan used an alternative conception that <u>aluminum foil absorbs radiation/light energy</u>. Since this was an alternative conception, the researcher continued to ask questions, specifically referring Dylan to the radiation lab with the lights shining on materials.

Researcher: So did the aluminum foil get really hot when it was on top?
Dylan: Not as much any other ones.
Researcher: So maybe aluminum foil wouldn't be the best on top. But what, maybe, would be good on top?
Dylan: *(looks at radiation data table still on front white board)* Um, white felt?

The first conversation ended with Dylan writing, "white felt" under "Top View" for her first design idea. From this interaction, it seemed that Dylan was using the conception that *the white felt had the largest temperature increase in the radiation lab*. The researcher left to check in with other members of the student team. While the researcher was gone, Dylan wrote, “copper wire” under “Side View” for her first design idea.

When the researcher returned, she and Dylan had a conversation about what material to put on the bottom of the cooker container for Dylan’s first design idea. The researcher reminded Dylan that there was a heating pad at the bottom of the solar oven and then asked what material she should put on the bottom. Dylan looked at the radiation lab data table on the front white board and responded, “Transparency?” In other words, she was using the alternative conception, <u>transparency sheet is a good conductor because it had the highest temperature increase (during the radiation lab)</u>. The researcher reminded Dylan that those data were from the radiation lab with the light. Dylan looked at the Materials Cost List and said, “Aluminum foil?” The researcher was unsure if Dylan had correctly chosen a metal because they are conductors, or if she had just guessed a material. Therefore, the researcher followed up by asking, “What does aluminum foil, is that a heat, does that conduct or does that insulate?” Dylan responded, “Insulate,” using the alternative conception that <u>aluminum foil is an insulator</u>. The researcher used the analogy of a stove and putting materials on a stove. She asked, Dylan, “Which of these materials would help conduct the heat to the fish?” Dylan responded, “Um…maybe the black felt?”, saying that <u>black felt is a conductor</u>. The researcher used a different version of the analogy of cooking on a stove, and Dylan could not answer. Finally, the researcher directly asked, “What are pots and pans made of?” and Dylan responded, “Metals.” The researcher reinforced this idea, that metal conduct heat on a stove. Again, the researcher asked what Dylan might want on the bottom of the cooker container. Dylan stared at the Materials Cost List for a bit and then responded, “I feel like maybe aluminum foil.” The researcher responded that choice was a good idea, and Dylan wrote, “aluminum foil” under “Bottom View” of the first design idea. It is unclear whether Dylan based her answer on the conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators),* or whether she guessed.

Dylan completed her other two design ideas herself, again just listing materials rather than drawing or including a justification. For her “Top View” materials, she chose “transparency sheet” for the second design idea and “black felt” for the third design idea. Because her three ideas for “Top View” materials (i.e., white felt, transparency sheet, and black felt) were the three materials that had the largest temperature increases during the radiation lab (and when she chose white felt for the first design, the video showed her looking at the table), it seems that she used the radiation lab data table to determine her "Top View" materials. In other words, in order to choose materials that would directly face the lamps in the solar oven, she used the correct result that *white felt, transparency sheet, and black felt had the largest temperature increases in the radiation lab*. The remainder of her choices are less clear. For the "Bottom View," she wrote, "Wood," which is an insulator, for the second design and nothing for the third. In the pros and cons analysis, she wrote that wood "would be great and work perfectly," which is not specific enough to determine a scientific or alternative conception. For her "Side View" materials, she wrote "copper wire," "pipe cleaner," and "paper clip" for each design idea. She did not justify her choices of copper wire or pipe cleaner, but she explained that the paper clip "would make it stay in place" in the pros and cons analysis. From this, it can be inferred that her choices for "Side View" materials were likely based on her ideas about the structure of the cooker container, not its thermal properties.

In her pros and cons analysis of the three design ideas, Dylan had one pro and three cons related to heat transfer. She wrote the white felt "will heat up correctly," the aluminum foil might "burn the fish," the transparency sheet "might heat up too fast," and the black felt "might not heat up at the right temperature." Taken together, these statements are less about conceptions related to heat transfer and more that Dylan had a fundamental misconception about the criteria of the engineering challenge. Rather than trying to increase the temperature of a fish inside the cooker container prototype as much as possible within 10 minutes, she seemed to be more worried about reaching (and not overreaching) a specific temperature. Although this idea reflects the nature of cooking in everyday life – that food needs to be cooked correctly or else it might burn – it does not reflect the criterion given in the engineering challenge.

The main activity in Lesson 8 was for teams to select one design idea and explain and justify their idea using an evidence-based reasoning graphic. This was still part of the plan (a solution) step of an engineering design process, since planning includes both idea generation and idea selection. During the activity, the student team had several discussions to review the problem and decide on one design idea. Then, they filled out one evidence-based reasoning graphic as a team, though Noelle took the lead on writing and drawing.

First, the student team discussed and filled out the "Problem with Criteria & Constraints" section of the evidence-based reasoning graphic. They demonstrated a fairly correct understanding of the engineering challenge, writing "a container to put inside a solar oven so they can be in the market while earning money" for the problem, "to cook the fish the fastest way in ten minutes" for a criterion, “the materials” for a constraint (i.e., they could only use the materials on the Materials Cost List.) Mr. Parker introduced the term, “Simplifying Assumptions,” as “the things that might be important but you have decided not to worry about,” which was the next section of the evidence-based reasoning graphic. The student team discussed a few possible simplifying assumptions that were not related to heat transfer ideas. They also discussed one possible simplifying assumption related to heat transfer.

Sheldon:	How hot it gets inside the solar oven, like the sun’s radiation.
Noelle:	It has to take in the sun’s radiation or the container won’t work.
Sheldon:	No, how hot the solar oven gets, though. *[inaudible]* only if it works also.
Marie:	Well, we would have to worry about that because if it doesn’t absorb enough light, then it won’t…
Noelle:	Well, um…
Sheldon:	Well we, they never said anything about the solar oven, how hot it gets.
Researcher:	Wait, so I think, I feel like we're talking about two different things here. We’ve got how hot the solar oven itself gets, versus how hot the fish in the container gets.
Sheldon:	The solar oven.

Sheldon was trying to say that they did not need to worry about the exact temperature inside the solar oven, which would have been an acceptable simplifying assumption. However, Noelle and Marie interpreted his statement as him trying to say they did not have to worry about radiation, which they disagreed with. They emphasized that they container needed to absorb light, or “take in the sun’s radiation,” or else it would not work. These statements are based on the scientific conception that *radiation is the transfer of heat across space in the form of light waves*. Sheldon, Noelle, and Marie’s ideas were each correct, but because they were not successful at communicating them with each other, they did not reach an agreement about whether the temperature inside the solar oven was a simplifying assumption or not.

After completing the “Problem with Criteria & Constraints” and “Simplifying Assumptions” sections of the evidence-based reasoning graphic, the student team began discussing the individual design ideas they had generated so they could choose one design for a prototype cooker container. At first, only Sheldon and Noelle participated in the discussion, with Marie and Dylan not contributing ideas. Sheldon and Noelle first agreed that the shape of their cooker container would be a box. These two members of the team also agreed to put aluminum foil on the bottom, with Noelle saying, “since it’s good at conducting,” and Sheldon saying, “because it’s good at conduction.” Here, Sheldon and Noelle appropriately applied the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* to their cooker container design. Noelle proposed lining the inside of the container with wooden sticks, "so it can stand," and also, "because wooden sticks are good at absorbing because it's a type of wood." Noelle's desire to use wood sticks to make the container sturdy is an acceptable design feature; however, her statement about wood absorbing is based on the alternative conception that wood absorbs radiation/light energy, which is conjectured to be based on the results of the radiation lab as explained above. Sheldon did not agree or disagree with her idea to use wood sticks, so Noelle added wooden sticks to her drawing of the team's cooker container within the "Design Idea" section of the evidence-based reasoning graphic. Noelle and Sheldon then discussed possible materials for the top of the cooker container.

Noelle: And then, oh! White felt on the top because it's good at…
Sheldon: That's what I put.
Noelle: Yeah.
Sheldon: And then white felt because it was the hottest in the solar oven things. And then for the other one [design idea], I put foil on the bottom and transparency sheet on the top because transparency, you can see through it to see the fish cooking and it was the second highest in the solar oven things with the cups.

Here, when Sheldon said the "solar oven things," he was referring to the radiation lab, since heat lamps were used in the radiation lab and also the solar oven. Noelle did not have a chance to finish her justification for white felt, but Sheldon supported his answers of both white felt and transparency sheet with data from the radiation lab, using the conception that *white felt and transparency sheet had the largest temperature increases in the radiation lab*. After this conversation, Noelle and Sheldon agreed that the top should be white felt. Noelle summarized their ideas thus far, saying, "We would put the aluminum foil on the outside and then line it with wooden sticks on the inside, so it would be able to stand and everything, and then white felt on top." In this statement, Noelle had included aluminum foil not just on the bottom of the container but also the outer sides of the container, an idea that the team had not previously discussed. At this point, she did not explain why she added this idea, nor did anyone on the team comment on it. Sheldon and Noelle then discussed using transparency sheets as windows to view the fish cooking, which was unrelated to heat transfer.

At this point in the discussion, Marie spoke for the first time.

Marie: I have an idea where we would line it all with black felt on the inside. And then on the sides, do all wooden sticks and on the bottom to make it sturdy. And then put the transparency sheet in the black felt, so it doesn't, so the fish don't touch the black felt. And then, cause the transparency sheet will help the fish not touch the black felt and it's good at absorbing, and then put the fish in. And then cover the top with a transparency sheet because it's going to reflect or absorb light to make it hotter.

The team agreed that wood sticks were a good idea, and then Marie and Noelle continued discussing Marie's ideas as Noelle continued to ask Marie to clarify her ideas.

Marie: I think, for the inside, we should do it all black, just because it's good at absorbing light. And then put transparency sheet around, and then put the fish in, and put the transparency sheet on top.
Noelle: So instead of aluminum foil, it would be black felt.
Marie: Yeah, because that's the best at absorbing light because it's darker.
Noelle: Or we could do white felt.
Marie: He [Mr. Parker] says that the black felt…
Noelle: Usually it's black felt.
Marie: Yeah, and something happened with the white felt.
Noelle: So the sides would be lined with wooden sticks, and then black felt would be on the outsides?
Marie: No, black felt would be on the inside.
Noelle: Oh, okay.
Marie: And then we're gonna line the black felt with transparency sheet because we don't want the black felt touching the fish because that's gross.

Marie used several conceptions related to heat transfer during this discussion. When Marie first explained her idea, she proposed using a transparency sheet on top of the container "because it's going to reflect or absorb light to make it hotter." Marie was correct that a transparency sheet on top would "make it [the fish] hotter" because *the transparency sheet had a large temperature increase in the radiation lab*. However, she did not identify the correct method of transmission, instead using the alternative conception that <u>the transparency sheet reflects or absorbs radiation/light energy</u>. In the subsequent discussion, Marie suggested lining the inside of the container with black felt "because that's the best at absorbing light because it's darker," which is based on the scientific conception that *dark colors absorb radiation/light energy better than light colors*. She and Noelle then briefly discussed whether light or dark materials actually absorb light better, addressing the unexpected results of the radiation lab in Lessons 4 and 5. By the end of the conversation, Noelle was convinced to put black felt on the inside of the container, so she added it to the drawing on the evidence-based reasoning graphic. Although Marie also mentioned lining the black felt with more transparency sheets "because we don't want the black felt touching the fish because that's gross," no other teammates commented on the idea, and Marie did not bring it up again.

After this clarification discussion between Noelle and Marie, Noelle made an interesting statement before being cut off by Mr. Parker, who was making a whole class announcement.

> Noelle: Well, for insulation, what do you want to do? We could put aluminum foil on the outside, and then wooden sticks, and for the insulation we could do black felt. So it's, but I feel like that would be really expensive, though.

Here, Noelle had combined her previous idea with putting aluminum foil on the outside of the sides with the team idea of wooden sticks and Marie's idea of lining the inside with black felt. Similar to before, she did not explain why she wanted to put aluminum foil on the outside of the container. The interesting component is that she said, "for the insulation we could do black felt." Noelle was correct in that *black felt is an insulator*. What is unclear is why Noelle wanted to include insulation in the cooker container at all, given that the goal of the cooker container was to increase the temperature of a fish placed inside the container. Unfortunately, Mr. Parker made a whole class announcement after this statement, and no one on the team followed up on this comment about needing insulation after the announcement.

The student team spent the next 17 minutes discussing their design plan for their cooker container prototype; however, this discussion contained very little talk about heat transfer. Mr. Parker gave each team a model agar fish, which the team then used to figure the dimension of their cooker container, as well as how many pieces of each material they would need. They briefly discussed whether to use white felt, transparency sheet, or both for the top of their container, and they agreed to use white felt with a transparency sheet window. Much of the 17 minutes was spent discussing how they would create a latch for the lid and handles for the sides of the cooker container. They debated various materials to use and methods of construction, ultimately deciding to purchase a steel washer, jumbo paper clip, and pipe cleaner. During this longer discussion, Noelle twice asked if they really even needed a handle, with Marie responding, "You don't want to burn your fingers, do you?" and, "How are we going to get it in and out without burning ourselves?" Here, Marie was referring to her previous experiences with cooking, where hands or pot holders are necessary so that people do not burn themselves. However, for this engineering challenge, Marie was vastly overestimating how hot the containers would get, though she did not know that yet since they had not tested the containers.

The other major topic of conversation during the 17 minutes was how many wood craft sticks to purchase. The student team's first method of estimating how many craft sticks they would need yielded a quantity of 40. When Mr. Parker came to check in with the student team, he immediately noticed and asked about the quantity of craft sticks.

Mr. Parker:	So what are the craft sticks being used for? Can you explain that to me?
Marie:	To hold up the, thingy.
Noelle:	So on the outside there's gonna be aluminum foil, and then the craft sticks are gonna be on the inside because they're good at absorbing.

It is unclear whether Mr. Parker heard or understood Noelle's statement related to the alterative conception that <u>wood absorbs radiation/light energy</u>. Regardless, he chose to focus on the number of craft sticks the team had written in their plan, helping the team realize that 40 craft sticks was an overestimation. They ultimately decided to request 10 craft sticks.

Mr. Parker gave the class their next prompt that they were to answer individually in their engineering notebooks: "Which solution did your team choose and why? Provide evidence for your reason." The student team's responses are in Table 4.6.

Table 4.6. *Students' notebook entries responding to the prompt, "Which solution did your team choose and why? Provide evidence for your reason."*

Student	Notebook entry
Marie	We chose the solution of making the inside all in black felt and line the sides with craft sticks and over top the craft sticks we are putting Al foil and making and topper using a pipe cleaner and a washer.
Sheldon	We chose to combine all of our solutions together, because they all had good ideas.
Noelle	We combined all of solutions together. We took my craft sticks to hold it, Sheldon's hook to open it, Dylan choose the white felt on top and Marie choose the Black felt for the inside.
Dylan	We chose the solution of putting the popsicle sticks and aluminum foil on it to heat it up for the solar oven.

Marie described the materials and structure of the cooker container without answering the "why" part of the prompt. Sheldon and Noelle both explained how they chose a solution by writing that they "combined all of our solutions together." In other words, they justified their decision-making by referring to including everyone's input. Dylan was the only team member to use any vocabulary related to heat transfer in her response, though her response was fairly broad. None of the students on this team specifically justified any of the material choices or cooker container structure in their responses to this reflection question.

This prompt was supposed to be the last activity in Lesson 8, so Mr. Parker and much of the class moved on to Lesson 9. Before teams could gather materials to begin building their prototypes, Mr. Parker checked to see that they had completed the evidence-based reasoning graphic. Most teams in the class had done so. However, the student team had not written anything in the “Data/Evidence” or “Justification” sections of their evidence-based reasoning graphic, so they had to finish this Lesson 8 task before they could start Lesson 9.

Noelle quickly finished the “Design Idea” and “Data/Evidence” portions of the evidence-based reasoning graphic herself. These parts are shown in Figure 4.5.

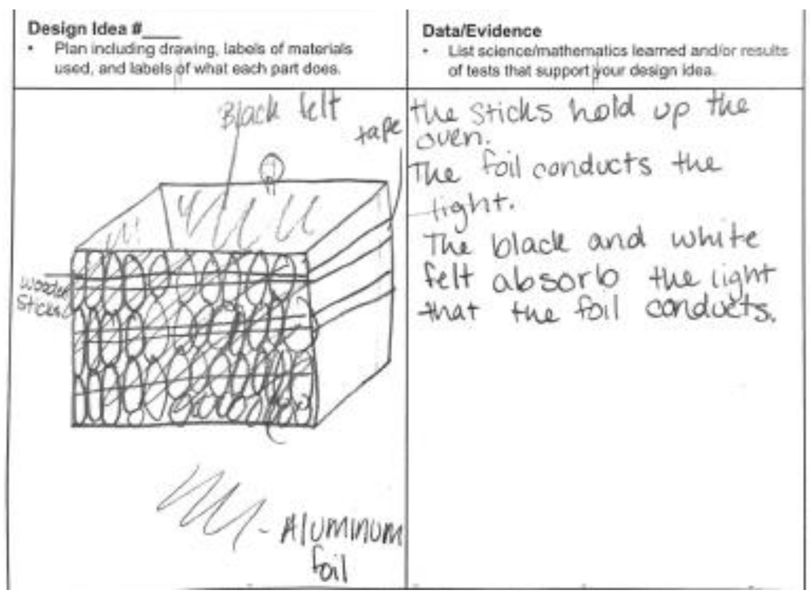

Figure 4.5. The “Design Idea” and “Data/Evidence” portions of the student team’s evidence-based reasoning graphic. Because the team rushed to finish filling out this document, the Design Idea drawing is incomplete (e.g., it is missing any indication that the team had decided to use white felt and transparency sheet for the top), and the “Data/Evidence” section was only done by Noelle without input from other team members.

Noticing that Noelle had completed the “Data/Evidence” section by herself, the researcher read aloud what she had put. The rest of the team did not add to or refute any of the statements. The statement that “black and white felt absorb the light” is likely based on the scientific conception that *dark colors absorb radiation/light energy* and the fact that *white felt had the largest* *temperature increase in the radiation lab*. However, Noelle twice used the idea that "aluminum foil conducts light," which is an alternative conception that combines ideas and vocabulary from conduction and radiation. Foil is a metal and therefore a conductor, but it does not make sense to use the terms conduct or insulate with respect to light. In terms of its interaction with light, aluminum foil reflects light. However, because Noelle chose to place aluminum foil on the outside of their container, it seems that she thought that the light energy would be absorbed by the aluminum foil and then conducted to the interior of the container. These statements, combined with the choice to cover the outer sides of the container in aluminum foil, indicate that Noelle was using a mix of scientific and alternative conceptions in this portion of the evidence-based reasoning graphic.

This mixture of conceptions carried through to the "Justification" portion also, although here the student team all contributed. Noelle read the full prompt, "Why do you think this design will work? Explain how your data and evidence support your design idea in order to meet criteria or constraints." The team agreed that, "It was simple, easy, and durable," which Noelle wrote down. The researcher prompted them to think deeper.

Researcher:	Why do you think it will work? Why do you think it will heat up the fish?
Noelle:	Because, just, all that heat and everything. And we have the aluminum, and the black felt…
Dylan:	Because I think the temperatures are good for what we're using them for.
	(As Noelle writes, she asks how to spell "radiating.")
Noelle:	Radiating, all the heat and light that is radiating…to?
Marie:	To the black felt.
Noelle:	To the aluminum, "to the foil and felt will absorb…" Wait, no, that doesn't make sense. "All the heat and light that is radiating to the foil and felt will absorb…"
Marie:	And heat up the fish.
Noelle:	"…and conduct to the fish." Does that make sense, you guys?
Marie:	Yeah.

Ultimately, Noelle wrote, "All the heat and light that is radiating to the foil and felt will absorb and conduct to the fish." Similar to what she had written for "Data/Evidence," this statement in the team's "Justification" is an alternative conception that combines ideas and vocabulary from conduction and radiation. The team was able to state various heat transfer terms, but it seems that they do not have fully scientific conceptions of what these terms mean in the context of their engineering design solution.

There is one additional design feature that indicated a mix of scientific and alternative conceptions. Multiple times, the team was able to scientifically support their choices of individual materials: black felt should be used on the interior of the container because *dark colors absorb radiation/light energy*, and white felt and transparency are good top materials because *white felt and transparency sheet had the largest temperature increases in the radiation lab*. However, no one on the team noticed that by placing a piece of white felt (with a small transparency window) on top of the cooker container, very little radiation would transmit through to the interior, and therefore the black felt interior would not be able to absorb much radiation. In other words, the team used some scientific conceptions to support their selection of individual materials, but it was evident that they did not have fully scientific understandings of radiation because of the way they chose to combine those materials in their design plan.

4.2.2.2 Lesson 9: Trying/building the first prototype.

In Lesson 9, students completed the try (the plan of the solution) step of an engineering design process. In other words, they build their cooker container prototypes. Although the student team talked amongst themselves for almost the full ~1.5 class periods that this lesson took, they made very few statements related to heat transfer conceptions.

After Mr. Parker confirmed that the student team's evidence-based reasoning graphic was complete, they were allowed to collect their materials. They had a brief discussion about which color of pipe cleaner to choose, ultimately choosing the sky blue one because "that's pretty." Once they had their materials, they delegated tasks to different team members: Sheldon worked on the top with the white felt and transparency sheet, Marie cut the black felt and aluminum foil side pieces to the correct size, and Noelle and Dylan marked, cut, and assembled the wood craft stick pieces into four walls. As they constructed their cooker container prototype, the student team conversed, but their discussion was mostly about the structure of the container.

There were a few times that heat transfer conceptions were used, usually as a response to a clarification question from the researcher or a teammate. The first set of heat transfer conceptions were used when the student team thought about the black felt, wooden sticks, and aluminum foil of their wall structure. The researcher asked what the black felt was for; Marie said it would be on the inside, and Noelle replied, "Insulation." Later, the researcher also asked about the aluminum foil.

Researcher:	So what is the foil for?
Marie:	The insulation.
Noelle:	No, this [black felt] is for the insulation. That [aluminum foil] is on the outside.

When the researcher clarified that the foil was supposed to go on the outside of the wood sticks, Marie said, “To make the light reflect,” and Noelle agreed. Later, when each wall piece was assembled as a line of wooden sticks with aluminum foil on the outside and black felt on the inside, Marie explained the team’s materials choices.

Marie:	So it’s sturdy. We’re only using these things [wood sticks] for the sturdiness. And then we’re using this [black felt] for, that’s the insulation. And this [aluminum foil] is just to make it hotter, I think. I’m not really sure.

Once the four walls were assembled and taped together, Marie and Noelle noticed that in the process of assembling the walls, much of the foil and felt was covered in tape. Marie said, “So how’s it going to reflect if there’s tape all over it?” Noelle and Marie agreed to add a second layer of aluminum foil to the outside, this time using the tape only on the back of the foil so that the full surface of the foil was exposed. They debated doing the same to the inside, adding another layer of black felt with tape not visible. Noelle said, “I feel like it’s gonna be too thick then, you guys,” and Marie countered, “I don’t think so because if the tape’s covering it, it’s just going to block the absorption.” The two students discussed it further, with Marie saying, “It’s not gonna absorb light because there’s too much tape in there!” and Noelle still concerned that “it’s gonna be too thick.” Dylan supported adding another layer of black felt, saying “Actually, I think it would help,” so the team agreed to add a second layer of black felt to each interior wall.

These statements about the wall structure of their cooker container prototype show that the student team used several scientific conceptions but had difficulty applying them to their design correctly. After Noelle first mentioned it, Marie also said that *black felt is an insulator*. Also, Marie explained their decision to put aluminum foil on the outside of the walls by saying that it would reflect light, which is based on the scientific conception that *metals reflect radiation/light energy*. Although of these conceptions are correct scientific conceptions, they were applied in such a way as to make a poor design. Because the aluminum foil was on the outside of the container, it would reflect light away from the container; similarly, it is not clear why Marie and Noelle wanted to create an insulated container given that the goal was to maximize the inner temperature increase.

Another justification for the black felt interior was that it would absorb light, which is correct given that *dark colors absorb radiation/light energy*. However, neither Marie nor Noelle realized that the black felt would not be able to absorb much light since the top of the container would mostly be covered by white felt (with a small, clear transparency sheet window). Noelle and Marie understood basic conceptions about thermal properties of materials but struggled to apply them appropriately.

There were also a couple of comments about the bottom of the container that were related to heat transfer. Marie did not remember what the team had decided for a bottom, so she asked, "What is our bottom? Popsicle sticks?" Noelle replied, "The foil." Later, she explained why, "Aluminum foil cause it's a good conductor." This seemed to convince Marie, and when Mr. Parker checked in on the team and asked about their bottom material, Marie replied, "Aluminum foil." During the individual idea generation writing and team idea selection discussion, Marie had ignored that conduction would occur at the bottom of the container where the heating pad was, instead focusing entirely on radiation. However, Noelle had consistently kept that aspect of the solar oven in mind, proposing they use aluminum foil as a conductor since *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. This conversation seemed to prompt Marie to think about the conduction happening at the bottom of the solar oven.

The student team reached a point where they thought they were done building their cooker container prototype. The researcher asked them to "pretend that I am the client and tell me how your design is going to work."

Marie:	You open, okay, you have a little handle, see. *(Marie points to the handle)*. Handle. Flip it open, easy to get the fish in and out. *(Marie opens the lid and mimes putting in and removing a fish.)* Check on your fish. *(Marie points to the transparency sheet window on the top.)* And it's [white felt] a good conduct-, yeah, conductor?
Sheldon:	Yeah, cause then, then the radiation can actually hit the black felt inside too. *(Sheldon points to transparency sheet window on top)*
Noelle:	And the aluminum- *(Noelle points to the aluminum foil exterior sides.)*
Marie:	Aluminum foil is a good conductor.
Noelle:	And wood and the black felt are good at absorbing.
Marie:	And the wood helps it keep it sturdy so it stands. And then this one *(points to the aluminum foil bottom)* is good at conducting, so when you put the fish in there-
Noelle:	On the heat pad.
Marie:	Yeah. It [aluminum foil] reflects light, and it makes it hotter. Ta-dah!

The student team continued to use scientific and alternative conceptions that they had generated earlier in Lessons 7 and 8. Marie's statement that white felt is a good conductor stemmed from the team using radiation lab data to answer a question about conduction. Noelle continued to use the alternative conception that wood absorbs radiation/light energy, while Marie continued to focus on wood making the structure sturdy without thinking about the thermal properties of wood. Noelle said that black felt is good at absorbing, which is based on the conception that *dark colors absorb radiation/light energy*. For the first time, someone on the team pointed out how the black felt would absorb radiation, given that most of the top of the container was white felt. Sheldon pointed to the small transparency sheet window, saying, "then the radiation can actually hit the black felt inside too." Sheldon was correctly using the scientific conception that *clear materials transmit radiation/light energy*. Earlier, Noelle and Marie had always discussed black felt absorbing light without any consideration of how much light the black felt would actually be exposed to; here, Sheldon explained that the radiation would reach the black felt interior through the small transparency sheet window on top.

Marie and Noelle used two scientific conceptions about aluminum foil, that *metals reflect radiation/light energy* and that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*, though they applied them to the design with varying correctness. They said that "aluminum foil is a good conductor," when referring to the exterior walls of the container, which was an incorrect application since the walls would experience heat transfer via radiation, not conduction. They agreed that aluminum foil on the bottom "is good at conducting," which was a correct application since the bottom would experience heat transfer via conduction because of the heating pad. Marie also said that the aluminum foil, "reflects light, and it makes it hotter." It was unclear whether she was referring to the aluminum foil exterior walls or the aluminum foil bottom when she said this. Either way, it was an incorrect application of a scientific conception, since reflecting light away from the container would not make it hotter.

After the team thought they were done, they discussed a few more concerns and acted on one of them. The one that the acted upon occurred after Noelle said, "Now that I realize it, won't the heat escape when, since this [the top] isn't closed?" Although she did not explicitly relate this statement to convection, she seemed to be basing her concern on the scientific conception that *hot fluids rise*. The team agreed that this might be a problem, and so they decided to seal the top shut with tape after the fish was placed inside but before the container was put in the solar oven.

The other concerns that were expressed did not change the cooker container prototype. Noelle was still concerned about the thickness of the container's walls, saying, "I feel like it's just layered and layered; it's really thick." Once she saw the entire container put together, Marie expressed concern about the top of the container.

Marie:	I feel like we should have made the hole bigger. *(Marie circles her finger around the transparency sheet window in the white felt top piece.)*
Noelle:	Be careful with it, Marie.
Marie:	Yeah, I know.
Researcher:	Why do you think you should have made the hole bigger?
Marie:	So light, so more light can get into it.

When asked by the researcher what that process is called, Marie first answered, "radiation," but then clarified, "transmit light." Here, Marie correctly used the scientific conception that *clear materials transmit radiation/light energy* when identifying a potential problem with the cooker container prototype, which was that they only had a small section of clear transparency sheet and therefore not much light would be transmitted.

The student team's completed cooker container prototype is shown in Figure 4.6.

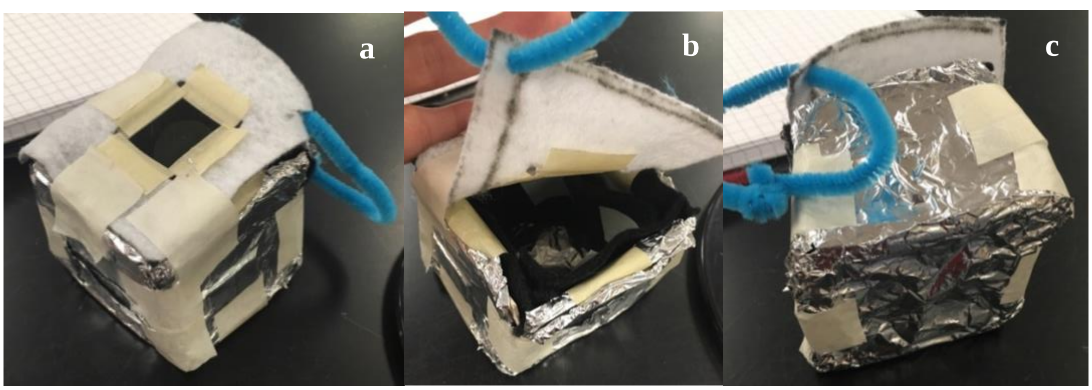

Figure 4.6. The student team's initial cooker container prototype, showing a) the top view with the lid on, b) the interior, and c) the bottom of the container.

It had an aluminum foil bottom, and the walls were wooden sticks covered in two layers of black felt on the interior and two layers of aluminum foil on the exterior. The top was a piece of white felt with a transparency sheet window in the middle, along with a pipe cleaner handle; although it is not visible in Figure 4.6, the student team sealed the top with tape after the fish was inside.

4.2.2.3 Lesson 10: Testing and deciding about the first prototype.

In Lesson 10, students completed two steps of an engineering design process: test (the solution) and decide (about whether the solution is successful). The students tested their cooker container prototypes by placing a model agar fish inside and then putting the containers in the classroom solar oven for 10 minutes. All teams shared their temperature increase and cost data with the rest of the class, and Mr. Parker led a discussion about the performance of the cooker container prototypes. The students discussed in their teams and wrote the answers to eight questions that were meant to help the students evaluate, or decide about the success of, their initial design. During these engineering design process steps of test and decide, the student team attempted to use heat transfer conceptions to explain why their prototype performed poorer than they expected and how they could improve for the next design. The entire student team was present on the day that they tested the prototypes and answered the first three evaluation questions. However, Noelle was absent for the last five evaluation questions, so the team did most of the decide (about whether the solution is successful) step without her.

In order to test (the solution), Mr. Parker first passed the one model agar fish to each team. Although Sheldon wanted to measure the temperature of the fish using the digital temperature probe, Marie and Noelle decided to let Dylan do it because she had not participated much in other activities. At first, Dylan held the probe near the tip, which prompted Sheldon to say, “It’s going to be the temperature of her hand!” and Marie to say, “No, that’s going to transfer heat.” The team then helped Dylan adjust her grip on the probe so that her hand was farther away from the end. Dylan measured an initial fish temperature of 18°C, which was the same starting temperature as the other fish used by the other five teams in the class. The student team then loaded the fish in the container and taped the top shut, sealing the container. Mr. Parker placed all six cooker container prototypes into the solar oven for 10 minutes, during which time the heat lamps and heating pad were turned on. After the 10 minutes, Mr. Parker removed the containers, allowing each team to measure the final temperature of their model agar fish. Sheldon was chosen to measure the final temperature; he did so by fully opening the top lid of the team’s cooker container prototype and using the temperature probe while the fish was still inside.

Sheldon returned to the rest of the student team with the fish, temperature probe, and cooker container prototype, and he told them the final temperature of the fish.

Sheldon: 32 [degrees Celsius].

Noelle: Are you sure? I thought that was going to work better.
Marie: Yeah, me too.
Marie: Is it hot? *(Marie feels the outside of the container.)* Yeah, it's warm.
(Dylan and Noelle also feel the outside of the container.)

It is interesting that the three team members felt the outside of the container, but none felt the inside of the container or the fish, which is what was actually measured. The student team was disappointed and surprised that their fish only had a temperature increase of 14°C. Sheldon said, "I should have done this," showing the team that he should have barely opened the top of the container to insert the temperature probe rather than opening the lid fully. It was implied that Sheldon was reflecting by using the scientific conception that *hot fluids rise,* since he realized that opening the lid a small amount would have let less hot air out of the container than opening the lid fully. The student team also started to look around at the other teams' cooker container prototypes, asking the other teams what their temperature increases were.

Marie and Noelle began discussing why their cooker container prototype did not perform as well as they thought it would. Noelle said, "Ours is probably too thick," which Marie agreed with. When the researcher asked them what they meant by that, Marie and Noelle pointed out all of the layers of the side walls: two pieces each of black felt and aluminum, plus a layer of wood. They then said, "It takes way too long to get hot inside." Noelle later explained, "It took too long to conduct. And so it didn't heat up the most in that amount of time. It would have to be in there longer to heat up more." Noelle correctly assessed that compared to most of the other teams, the *student team's container did not heat up quickly*. Her reasons for that result, that the container was "probably too thick" and "took too long to conduct," were likely correct because the thickness of their walls insulated the container. However, it was not clear that she meant that it took too long for thermal energy to conduct through the thick walls, or whether she was just using the term "conduct" as a broad term for any method of heat transfer.

Mr. Parker had created a whole class data table on the front white board. This table included the columns Team Name, Initial Temperature, Final Temperature, Temperature Increase, Cost, and Additional Characteristics. In the "Additional Characteristics" section, most teams wrote the materials included in their cooker container prototypes. A modified version of this table is shown in Table 4.7. The student team was represented by the team name of Swedish Fish, and Mr. Parker also included a "Control" fish that had been placed in the solar oven without a container.

Table 4.7. *Whole class data table from testing their initial cooker container prototypes*

Team Name	Temperature Increase	Cost	Additional Characteristics
Boiler Dawg's	13°C	$10.50	2x2x3 foil box with copper bars on the inside.
Swedish Fish	14°C	$26.75	Foil on the outside, black felt on the inside, white felt on top with transparency window.
The Agrious	15°C	$6.25	Transparency sheet on top with black felt around the sides. Then copper wire around the sides too.
Garbage	16°C	$14.50	Messily made of aluminum.
Funky Fishies	18°C	$18.00	Made of transparency sheet top, aluminum foil on bottom/sides [insides], popsicle sticks for support, white felt to absorb.
Nemo	22°C	$17.00	Transparency sheets all of the sides and a lid, coppers on the bottom, and a white paper [on top], and a lot of tape.
Control	16°C	--	No container

It is evident from the data in Table 4.7 that the student team's cooker container prototype did poorly when compared to the rest of the class. They had the highest cost in the class by far. Their cooker container's temperature increase was the second lowest it in the class, and it was two degrees Celsius lower than the control fish.

After all teams had recorded their data on the front white board, Mr. Parker invited the team with the highest temperature increase to share their prototype and why they chose the materials that they did.

Student: We used transparency sheets because when we did the cups, the transparency had the highest temperature. And we used copper at the bottom because copper is a metal and it *[unintelligible]* fast. We used a lid to keep the warmth in the container. And a lot of tape.

Although he did not ask any other team to share their prototype with the whole class, Mr. Parker pointed out some similarities between the top two designs: they both had metals on the bottom and both used transparency sheets on top. He also reinforced key heat points about thermal properties of materials, that metals are conductive and that the transparency sheet had a high temperature change during the cup (i.e., radiation) experiment.

Mr. Parker then gave the students the first three evaluation prompts, which the students answered individually without discussing as a team or a whole class.

1. Which cooker container prototypes had the largest temperature increase?
2. Describe why these cooker containers had a larger temperature change.
3. What are the results of your test? (Summarize)

For the first question, Dylan, Sheldon, and Noelle correctly identified that the Funky Fishies and Nemo teams had the largest temperature increase. Marie wrote, “the transparency sheet,” which was a description of the Nemo team’s prototype since the sides and most of the top were made of transparency sheets. For the second prompt, Marie basically repeated herself, writing “Because it was all out of transparency sheet,” without any further justification related to heat transfer conceptions. Sheldon also did not justify his answer for the second prompt, just writing, “They had copper wires.” Dylan agreed with Sheldon that copper wires were important, though she had a more thorough explanation, writing, “because they put the copper on the bottom and metal is copper wire and metal heats up fast.” Here, Dylan seemed to be basing her statement on the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. For the second prompt, Noelle wrote, “They had the larger temp change because they had very few materials and it was not as thick as ours.” This was consistent with comments made earlier, where Noelle was concerned about the thickness of the container but did not explicitly link those concerns to heat transfer conceptions.

The students on the team took different approaches to answering the third prompt. Noelle best summarized the results, writing, “Our start temp was 18°C and our temp increase was 14°C at the total cost of $26.75.” Sheldon’s answer that “It shows the cost and temperature before and after the change,” was not incorrect but too broad. Marie focused on cost, writing, “The cost of our cooker container is kind of ridiculous,” which was true given that their cooker container’s cost was much higher than other teams’. Dylan wrote, “Our results came out good but we spent too much on tape than we needed to.” The team had used 18 pieces of 6”x1” masking tape, which cost them $4.50, which was also high compared to other teams in the class. Thus, her statement about using tape was a correct evaluation. However, it is unclear why Dylan thought that the team’s results “came out good,” considering that they had the highest cost and second-lowest temperature increase in the class, and their temperature increase was less than the control. Her statement reveals a misunderstanding of the problem and the team’s performance.

The other five evaluation prompts occurred during the next day’s class. Mr. Parker implemented this activity by giving the students a prompt, allowing them to answer it individually in their notebooks, and then having them discuss their answers in their small groups. Noelle was absent on this day, so she was not involved in the discussion, and although she did have answers to the prompts in her notebook, it was because she later copied what Dylan had written. The remaining members of the student team had difficulty focusing on the evaluation prompts, either discussing ideas their ideas for the next design even when that was not the question they were supposed to be answering or sitting in silence with their heads on their desks. Also, Sheldon was the only team member to write responses to all five prompts.

The next prompt asked the students, "What have you learned about the performance of your solutions from the test results? Explain both the things that worked and did not work." Marie did not write anything, instead putting her head on her desk. Dylan wrote, "I learned that maybe it's better to put metal on the bottom to cook it right." Similar to her answer to the second evaluation prompt, Dylan based her statement on the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. However, her inclusion of the phrase "to cook it right" indicates that Dylan may still have had a misunderstanding about the problem in that she thought the goal was to reach a specific temperature, not to maximize temperature. Sheldon responded, "Our container was a little hotter than the control. We spent too much money." When he shared his answer with his teammates, they agreed that their cooker container was too expensive. However, Sheldon incorrectly interpreted the results when he wrote that the student team's container was hotter than the control. Although Marie did not write a response to the question, she contributed to the team discussion, saying, "I thought what worked well was the aluminum foil because it really conducted that heat. What I didn't think worked was probably, it was just too thick." The statement that aluminum foil conducts heat is correct in terms of the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. However, because Marie did not specify whether she was referring to the aluminum foil on the exterior sides of the container or the aluminum foil on the bottom, it is difficult to interpret whether she was using "conduction" as a general term or specifically referring to the conduction occurring at the base of the container where the base was in direct contact with the heating pad in the solar oven. Marie's analysis that "it was just too thick" is an acceptable evaluation, though she did not relate the thickness factor to any specific heat transfer conceptions. After Marie and Sheldon spoke, the team started discussing their next design, which is related to the next two prompts; therefore, this part of the conversation is included with those prompts.

The next two prompts were, “What changes will you make to improve your solution based on the results of the test?” and, “Why will you make those changes? Think about the results of the test and the science and math you have learned.” The three team members immediately agreed on two changes. First, they agreed that they needed to use fewer materials so they would spend less money, which is what Sheldon wrote as his response for the two questions. Second, they agreed that they needed to use copper wire because wire would “make it hotter.” At first, they agreed that the copper wire should be on the bottom of the container. Dylan wrote, “I maybe think a change could be putting metal on the bottom which would be copper wire,” During the discussion, Marie said, “I feel like copper in, at the bottom where the fish is,” and Sheldon began to describe making several loops of copper wire at the bottom. Marie added to Sheldon’s idea, proposing that they buy copper wire for the bottom and the sides. Sheldon looked confused, so Marie drew her idea in her engineering notebook.

Marie: Like, our is container is right here. And then wrap it around this way. *(Marie draws wire wrapped around the sides.)* And then wrap it down here. *(Marie draws a loop of wire on the bottom.)*
Sheldon: Why that way? It’s a conductor.
Marie: I know. We would wrap, I’m wrapping it on the sides.
Sheldon: Why would we put it up here where it’s not touching anything?
(Sheldon points to side copper wires in Marie’s sketch.)
Marie: Because so-
Sheldon: I was thinking wrapping it around the bottom, like on the bottom of the container.
Marie: Well, I don’t know.

Marie and Sheldon both agreed that “copper wire is a conductor,” which is part of the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. However, this discussion revealed a difference in how Sheldon and Marie thought about what conduction actually is. Sheldon demonstrated a scientific conception about conduction, which is that *conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas*. Sheldon realized that conduction occurs where materials touch, which in the case of the engineering challenge was where the bottom of the cooker container made contact with the heating pad that was part of the solar oven. In contrast, Marie seemed to have the alternative conception that <u>copper wire transfers heat quickly regardless of context (i.e.,</u>

no distinction between conduction and radiation). In this case, she thought that copper wires on the sides of the cooker container would conduct heat, even though the sides of the container were exposed to air and radiation from the heat lamps and not in direct contact with a heat source. The team ultimately agreed to use copper wire and aluminum foil on the bottom of the second cooker container prototype.

Marie and Sheldon also agreed to change the top material. Marie suggested, "And then instead of putting white felt on top, we just put a plain old transparency." Sheldon agreed, responding, "Yeah, a transparency sheet." The researcher asked them to explain why, and Marie responded, "Because it's gonna conduct more heat inside the thingy. Because at our data, when they [Nemo team] did all transparency sheet, they had the most, they had the highest temperature." Marie's justification was correct in the sense that *the cooker container with transparency sheet top and sides had the largest temperature increase during prototype testing*. However, she used incorrect vocabulary when she called this process "conduction," essentially saying that transparency sheet is a good conductor. Again, Marie seems to be basing her explanation on the alternative conception that conduction is the transfer of heat in any context since she does not seem to distinguish between conduction and radiation.

The team also discussed the side walls of the second cooker container. Marie proposed, "I think we should stay with the same design but not as thick. Don't put two layers of foil; only put one layer of foil. And one layer of black felt on the inside." The researcher asked, "So when you say the same, are you still thinking the wood sticks too?" This prompted a discussion in the team about whether or not to use wood sticks. Marie thought they were needed "because that's going to make it sturdy," pointing out that otherwise their walls would only be aluminum foil and cloth. Sheldon pointed to another team's cooker container prototype that appeared to have aluminum foil sides, saying, "[Other student's] didn't use any wood sticks but theirs stood up just fine." Sheldon also remarked that using a lot of wooden sticks "would just be a waste of time and money," and Marie replied, "No, no, because we're not going to buy us that much." Marie and Sheldon also discussed one feature of wooden sticks related to heat transfer conceptions.

Marie: The wood is a good conductor too.
Sheldon: So then let's put the wood only on the bottom, not on the sides also.

It is unclear where Marie's alternative conception that wood is a good conductor came from, since she had not used that conception before. (During Lessons 8 and 9, Noelle had repeatedly commented that wood absorbs radiation/light energy well, but no one had made a comment about wood being a good conductor.) Sheldon did not disagree with her, but he pointed out that if wood is a good conductor, then they should put it on the bottom where conduction will occur, not the sides. Here, he again demonstrated his understanding of the scientific conception that *conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas*, so conduction would occur at the bottom of the cooker container, not the sides. Marie eventually agreed to have wooden sticks on the bottom and not the sides, but she did so by rolling her eyes and saying, "Okay…", which indicated that she was not fully convinced.

For the final two evaluation questions about how the solution met and did not yet meet the criteria and constraints of the problem, the team did not speak nor write much. Sheldon wrote, "We made a container that heats up," and, "It is too expensive!!!!" Dylan wrote and spoke about the team performance, saying that the solution met the criteria because "when we don't agree, we talk it out, I guess." Marie wrote and said, "It needs to get hotter." Sheldon pointed out that at least their container was hotter than one other team's container, but Marie emphasized, "It still needs to get hotter." The team agreed that their next design needed to be cheaper and get hotter, which were appropriate goals given the temperature and cost results of their first prototype design.

The team then started to discuss other possible design components.

Marie: We need to put less materials on it, to make it really conduct heat. *(pause)* Actually, I think I have an idea. We could put the sides with just transparency, the sides could be all transparency sheet and then wood on the bottom and then aluminum foil on top.

Here, Marie was concerned that the team still had too many materials in their current second container design idea (i.e., aluminum foil, copper wire bottom, and wood bottom; transparency sheet top, aluminum foil and black felt sides). She thought that using fewer materials would "make it really conduct heat." In a general sense, this conception that *fewer layers of material (i.e., less thick) conduct heat better than more layers* is a scientific one. However, she still seems to be using "conduction" in a general sense that conduction is the transfer of heat in any context, not distinguishing between conduction (at the bottom of the container) and radiation (at the top and sides of the container. The design she then suggested was a mixture of good and poor components, though she did not explain her reasoning for any of them.

Her teammates did not agree or disagree with the new ideas for components of the container, but Sheldon reminded Marie that they needed the copper wire. The researcher asked where the copper wire would go.

Marie: The copper wire is going to be around the sides?
Sheldon: It has to be on the bottom.
Dylan: Yeah.
Marie: Oh, well, at the bottom, whatever.

Sheldon and Dylan agreed that the copper wire needed to be on the bottom of the cooker container, since *copper wire is a conductor* and *conduction occurs at the bottom of the cooker container*. Similar to the previous conversation about copper wire, Marie ultimately agreed with Sheldon and Dylan, though she still seemed unsure.

The student team started counting how many transparency sheets they would need. Marie and Sheldon disagreed on the number because Sheldon included a transparency sheet top instead of just the sides.

Marie: We're not putting it [transparency sheet] on top. We're gonna put aluminum foil on top.
Sheldon: Aluminum foil is a conductor.
(Dylan and Marie express confusion.)
Sheldon: Then the aluminum foil needs to be the bottom.
Marie: I was thinking wood, should we put wood on top then?
Dylan: Uhhh….
Sheldon: Wood's a conductor, though.
(Dylan and Marie express confusion. Then the team silent.)

Marie suggested two different materials for the top, aluminum foil and wood. Sheldon disagreed with both, saying that they were conductors and therefore needed to be on the bottom. The idea that *aluminum is a good conductor* is based on a scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators),* but the idea that <u>wood is a good conductor</u> is an alternative conception. However, he was consistent in applying the idea that *conduction occurs at the bottom of the cooker container* because *conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas*.

After some quiet thinking, Marie proposed another idea for their second prototype.

Marie: You know, we should, okay. It goes, aluminum foil on the bottom, and then transparency sheets on the sides, and then should we put black felt on top?
Sheldon: What was the black felt? No, white felt on top.

Marie: Black felt absorbs more heat.
Sheldon: Okay, black felt.
Marie: So then it'll be aluminum foil on bottom, transparency sheets on the sides, and then black felt on top.

Marie accepted the previously discussed ideas to have transparency sheet sides and aluminum foil on the bottom, though she did not justify these components at this time. She proposed a new idea for the top material, black felt, which she supported by saying, "black felt absorbs more heat." This idea is an appropriate application of the scientific conception that *dark colors absorb radiation/light energy*; by placing black felt at the top of the cooker container, it would absorb radiation from the heat lamps on top of the solar oven.

Mr. Parker then interrupted the small group discussions to end Lesson 10. In the last part of Lesson 10, he refined the criteria based on the whole class results. Instead of attempting to reach the highest temperature in 10 minutes, Mr. Parker told the students that their goal was to "reach a higher temperature than the control fish." Instead of meeting the general criterion of being low cost, he adjusted it to be a constraint of "under $10." He also commented that in terms of size of the cooker container, all teams created reasonably-sized prototypes, so that criteria did not need to be adjusted. He ended the lesson by reminding the class that these were now the goals for their second round of solution generation, or redesign.

4.2.3 Solution Generation Part 2: Redesign and Communication to the Client

The second solution generation stage of the *Ecuadorian Fishermen* curricular unit was redesign which included four steps of an engineering design process: plan (a solution), try (the plan of the solution), test (the solution), and decide (about whether the solution is successful). This second solution generation stage, or redesign stage, was implemented over approximately 2.5 class periods. Additionally, after the redesign, students wrote a letter communicating their best design to the client and also reflected upon the whole unit during Lesson 12. Mr. Parker implemented this final lesson of the *Ecuadorian Fishermen* curricular in approximately 1.5 class periods.

It is worth noting that winter break impacted the implementation of Lessons 11 and 12. The class completed the plan, try, and test (the solution) steps of the redesign process in Lesson 11 during the last class period before winter break. This meant that they did not decide (about whether the solution is successful) from Lesson 11 or do Lesson 12: Communicating with the

Client until after winter break. This multi-week interruption impacted their level of enthusiasm about and effort put towards the *Ecuadorian Fishermen* unit. Especially by the time the students did Lesson 12, there was a noticeable drop in effort in terms of amount written and spoken.

4.2.3.1 Lesson 11: Redesigning a second prototype.

During Lesson 11, the class completed all four steps of the solution generation stage a second time in order to redesign a solution. The student team had already discussed several ideas for their second prototype during Lesson 10, so they did not spend much time planning during Lesson 11. However, their redesign was more scientifically sound, so it performed much better than their first cooker container prototype. It is important to note that Lesson 11 started on the same say that Lesson 10 ended, which meant that Noelle was not present for the plan (a solution) and first part of try (the plan of the solution) steps of redesign.

As Mr. Parker talked about the importance of redesign, Sheldon and Marie quietly began to fill out the Redesign Materials Cost List together. They based their list of materials mostly on the last idea they had discussed during Lesson 10, with a couple of other ideas included: aluminum foil, copper, and wood sticks for the bottom; transparency sheets for the sides; black felt for the top; and a pipe cleaner for a handle. The researcher asked them to explain how they intended to structure the three materials on the bottom, and Sheldon explained that there were three layers, "So it's copper wires, craft sticks, and then aluminum." They realized this design would cost $12.50, so they agreed to use one copper wire instead of two, which brought the total cost to $10.50.

The researcher asked the team to explain more about the craft sticks, and Marie responded, "We're not putting craft sticks on the sides anymore because that's just gonna be a waste." The researcher then asked another question about the craft sticks on the bottom.

Researcher:	What do you think is going to happen with the heating pad if you have craft sticks on top of it?
Marie:	It would burn.
Sheldon:	Yeah, the wood would catch fire.
Researcher:	You're not gonna, it's not gonna get that hot.
Sheldon:	No, like, over down there [in Ecuador].
Marie:	Maybe we don't need, uh…
Sheldon:	When they [the fishermen] put it on the grill, when they put it on the oven, it'll catch on fire.
Marie:	Maybe we don't need the craft sticks.

Sheldon: Yeah, we don't.
Marie: Because it should stay sturdy.
Sheldon: Yeah, because [another team] way down there, they had a nothing.

After this conversation, Sheldon erased wooden craft sticks from the Redesign Materials Cost List. Sheldon and Marie decided to not use any wood craft sticks in their second prototype, though their reasons were not related to the fact that wood reflects light and is an insulator. Instead, they agreed that their design should be sturdy enough without the wood, since other teams did not use wood but had a durable prototype. Also, they thought that by having wood on the bottom, it might catch on fire and burn, which was an overestimation of the solar oven. Later during the discussion, Sheldon explained that they needed a pipe cleaner, "For a latch again, so they don't burn their fingers off!" Here, the team did not necessarily have an alternative conception about heat transfer, but they did have a misunderstanding about the solar oven context of the problem.

During this small group discussion, Mr. Parker stopped to talk to the team about their first cooker container prototype. He asked them why they thought their design did not perform well, and Marie answered, "Because there's too much stuff and it's too thick." Mr. Parker inquired further.

Mr. Parker: So you think, why being too thick, why do you think that limited the temperature?
Marie: Because-
Sheldon: Because it's harder for it [heat] to get through.
Mr. Parker: So it's acting like a conductor or an insulator?
Sheldon: Insulator.
Mr. Parker: So you think there, it was insulating from that heat to get in.
Sheldon: Too much, yeah.
Marie: Because we had two of these [black felt] and two of that [aluminum foil].

Although Marie continued to use the basic statement that the prototype was "too thick," Sheldon was able to relate that idea to a scientific conception about heat transfer, that *more layers of materials (i.e., thicker) are insulating because heat transfer via conduction is more difficult*. Mr. Parker then left the team.

Because she had not yet contributed much to the discussion, the researcher asked Dylan if she had any thoughts about the new design.

Dylan: I just agree that copper wires should be the bottom. I'm not really sure.
(Unrelated discussion as Sheldon talks to another team)
Researcher: Why do [you] like the idea of the copper wire?
Dylan: Because it could, because that'll heat up fast, and-

Sheldon: I know, but the copper wire is a <u>very</u> good conductor.
Dylan: Yeah. But it heats up fast and it'll, I just think it'll cook right.
Sheldon: We need the copper wire. We want it to get 100 degrees.

Dylan and Sheldon both used a version of the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* to explain why copper wire should be on the bottom. Although they both correctly applied a scientific conception to the design, they each also stated a misunderstanding about the engineering challenge and context. Since she said, "it'll cook right," Dylan still seemed to think that the goal of the prototype was to reach a specific temperature, not increase the highest temperature possible. Also, Sheldon's goal of wanting to reach 100 degrees indicated that he still overestimated how hot it was possible for the solar oven to get.

During the time, Marie had started to fill out the Redesign Plan worksheet. Her drawings of the container showed a bottom made of copper wire and aluminum foil, a black felt top, and transparency sheet sides. Marie then asked the team for help justifying their second design. First, Sheldon said, "Cause the team who got the highest temperature last time was all transparency," which Marie wrote. This justification was correctly based on previous results that *the cooker container with transparency sheet top and sides had the largest temperature increase during prototype testing*. (Although Noelle was not present when the team completed this worksheet, when she returned she made a similar remark, "I'm guessing most people did transparency, since the highest one was transparency last time.") The researcher then asked them to also explain the copper wire and aluminum foil on the bottom.

Sheldon: Because copper wire and aluminum foil are both metals, so they conduct super good.
Dylan: Yeah, basically.
(Marie was writing and did not hear what Sheldon and Dylan said.)
Marie: Copper wire is a good conductor, right?
Sheldon: Copper wire and aluminum foil are both metals so they are good conductors.

Marie wrote that the copper wire and aluminum foil "are very good conductors." The team again used the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. Finally, the researcher asked them why they chose the black felt for the top of the container.

Sheldon: Because it's a good conductor. I mean, uh…

Marie: It's good at absorbing light.
Dylan: Yeah.
Sheldon: It's a good con-, good convector. Convector?
Marie: I'm putting it's "good at absorbing light."

Sheldon struggled to use the correct term, first guessing "conductor" and then "convector," though he was not sure about either. However, Marie immediately identified that black felt absorbs light, which is based on the scientific conception that *dark colors absorb radiation/light energy*.

The team was satisfied with their Redesign Plan worksheet, so they left to retrieve materials for building the second prototype. The team had just started to construct their prototype when the class ended for the day. Noelle returned to class during the next day, so the team's try (the plan of the solution) step involved building the second prototype and explaining their design decisions to Noelle, since she was not present when they made them. Even then, very little of the 33 minutes that the team spent constructing their second cooker container prototype contained comments about heat transfer conceptions. Instead, the team mostly discussed how they were going to construct the prototype, asking each other questions and giving each other instructions about details such as dimensions and shapes.

When Noelle asked about the copper wire and aluminum foil on the bottom of the prototype, Sheldon explained, "We're putting copper on the bottom to keep it, because it'll heat up faster." He continued to consistently use the scientific conceptions that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* and that *conduction occurs at the bottom of the cooker container*.

Next, Noelle expressed concern about the black felt.

Noelle: See, the thing I'm afraid of it the black felt. I don't…
Marie: It's gonna absorb light.
Noelle: Last time we did felt, and…
Marie: It's gonna be on top, not on bottom.

Here, Noelle was concerned because the black felt did not work last time. Marie used the same scientific conception about black felt that she did during the initial design, that *dark colors absorb radiation/light energy*. However, in contrast to the first design, Marie was able to appropriately apply the conception to the second design by placing the black felt on top rather than on the interior walls of a container that was covered by a mostly white felt top.

Sheldon had cut the copper wire in half and coiled one half into a loop. He explained to the team, “I cut it in half because it was way too big.” Marie responded, “You should add more copper wire to it. The more copper wire, the more it’s gonna heat up.” Marie used the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. Sheldon then taped the large copper wire loop to the center of one side of the aluminum foil, with the intention that the copper wire would directly contact the heating pad. He showed this constructed metal bottom component to his teammates.

Sheldon:	I put that middle one [copper wire] on so we could set the fish there, and it’d heat up the fish right there.
Marie:	Okay.

(Sheldon points to where the copper wire is located under the aluminum foil.)

Sheldon:	So that way it wouldn’t fall through and it’s gonna heat up the fish quicker.
Researcher:	So you think if the fish is directly sitting on top of the copper wire, it’ll help?
Sheldon:	Yeah, and then there’s, like, copper wire surrounding it.

Sheldon continued to consistently use the scientific conceptions that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* and *conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas*. In particular, he applied these conceptions to the design of the bottom piece by creating a large surface area of copper wire (in a loop) for the fish to be placed on to maximize heat transfer via conduction. Later, when Marie put the model agar fish into the cooker container for testing, she made sure to align the fish with the loop, saying, “It has to be a certain way.” This action and statement indicate that she similar scientific conceptions to Sheldon.

During the 33 minutes of construction, Mr. Parker checked in on the student team twice. First, he asked, “Where you planning on using foil anywhere else, or just the bottom?” The student team answered, “Just the bottom,” and then Mr. Parker left. The second time, he asked, “It’s going to be a black top this time?” Sheldon affirmed this, and again Mr. Parker left. Mr. Parker did not ask the student team to explain their material or structural choices further in either interaction.

The final portion of heat transfer talk occurred toward the end of the try (the plan of the solution) step of an engineering design process. The team had agreed that once the fish was inside the cooker container, they would seal the container as much as possible by thoroughly taping the container shut. However, they were unsure how they would then measure the temperature of the fish if it was trapped in the container. Marie proposed cutting a small hole in the black felt top, "and then just stick the thermometer in there." Sheldon and Noelle did not like that idea.

Sheldon: But then wouldn't, if we make a hole before we stick the thermometer in, it'll, uh…
Noelle: The heat will leave.

Although neither student explicitly mentioned convection, they were both concerned that creating a hole in the top of the container would allow hot air to escape since *hot fluids rise*.

The student team's second constructed cooker container prototype is shown in Figure 4.7, with the model agar fish inside. The bottom of the container was made of aluminum foil and copper, with the copper in a loop underneath the aluminum foil. The walls were transparency sheets, and the top was black felt. The container was sealed with tape, and a small pipe cleaner handle was placed on the corner of the lid to help open and close the container without burning fingers. The design ended up with a final cost of $10.00, with $0.50 spent on two pieces of tape.

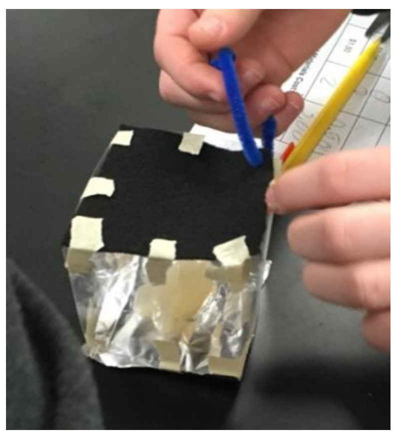

Figure 4.7. The student team's second design, or redesign, of a cooker container prototype.

Testing (the solution) step of an engineering design process was the last task the class completed before the class ended and winter break began. Sheldon measured the initial temperature of the fish, which was 19°C. Marie measure the final temperature of the fish, which was 41°C. When Marie reported the result to her team, Noelle commented, "Higher this time at least." However, because the bell had just rung, the student team left before anyone recorded the final temperature in their engineering notebooks. When the team returned after winter break, Marie thought that the final temperature had been 42°C, so that is what the team recorded. With that measurement, the student team calculated the temperature increase inside their second cooker container prototype to be 23°C. As a comparison, the first cooker container prototype had a temperature increase of 14°C. Also, the cost of the first prototype was $26.75, and the cost of the second prototype was $10.00.

Mr. Parker had made copies of each team's Redesign Plan worksheet, enough so that each individual student had one for their engineering notebook. He gave the students time to cut and paste these worksheets into their notebooks. While they were working on that task, he told them that the next activity was to compare the second design to the first, "So be prepared to answer questions about which one performed better and some reasons why you think it may have."

The student team agreed that their second prototype performed much better than their first prototype. Sheldon said, "the copper wire at the bottom kind-of helped," and Noelle added, "and the transparency sheets." The team also discussed the thickness of the first prototype.

Sheldon:	And then it's not as thick so it doesn't, it wasn't as insulated.
Marie:	And it's not as thick.
Noelle:	Yeah.
Marie:	It was horrible.
Noelle:	That one was like *(Noelle holds up fingers to show thickness)*
Marie:	It was a good inch.
Researcher:	Wait, Sheldon, you said something about insulating. What did you think was insulating?
Sheldon:	The first one was insulated, so it wouldn't, it wasn't really letting in heat.

Although the team agreed that the thickness of the first prototype was a poor design decision, Sheldon was the only one to connect that result to a heat transfer conception that *more layers of materials (i.e., thicker) are insulating because heat transfer via conduction is more difficult*.

Mr. Parker then presented the students with three evaluation prompts to help them decide (about whether a solution is successful). For each prompt, he gave the class time to answer the question individually in their notebooks, then discuss their answers as a team, and finally change their notebook answers if they wanted to. In contrast to the evaluation that occurred during the first round of solution generation, when the student team did not seem engaged and did not complete several of the prompts, during this round of evaluation all four team members answered the three prompts.

The first prompt was, "What are the results of your test?" All four team members wrote about the cost, that it was "lower cost" or "cheaper." Marie, Sheldon, and Noelle also mentioned temperature. Sheldon and Noelle said, "This one got hotter," and, "The second test had a higher temperature," respectively. Also, Noelle and Marie wrote the specific temperature change of 23°C. During the team discussion, they compared the two temperature increases – 14°C for the first prototype and 23°C for the second prototype – to determine that the second one "was almost 10 degrees hotter."

The second prompt was, "Did your redesign improve your solution? Why or why not?" Marie, Sheldon, and Noelle had similar answers in their notebooks. Their answers were essentially, "Yes it improved because it got hotter/had a higher temperature and was cheaper/had a lower cost." Dylan was the only one to write something about the materials, writing, "Yes because of the copper wire." During the team discussion, the researcher attempted to prompt the team to justify their answer to "why" with more detail.

Researcher:	What about the second part of that question, why or why not? Why do you think it improved?
Noelle:	It had a higher temperature increase than the first time, and the goal was to get the highest temperature in 10 minutes, so…that's the highest it went.
Researcher:	Why do you think it got a hotter temperature this time around?
Sheldon:	The copper wire.
Marie:	Because we used insulation.
Noelle:	We used way too much black felt and wooden sticks and aluminum foil last time.
Marie:	It was like an inch thick.

At first, Noelle again answered the "why" question by stating that the second design "had a higher increase than the first time," and she compared that to the criterion of getting the highest temperature increase in 10 minutes. When the researcher was more specific with the question, the team provided answers about materials that were not very specific. Sheldon said, "the copper wire," without discussing its thermal properties. Noelle and Marie agreed that the first prototype had too many materials and was too thick. Marie's comment, "Because we used insulation," indicated that she was now also making a connection between thickness and insulation, that *more layers of materials (i.e., thicker) are insulating because heat transfer via conduction is more difficult*. For the rest of the discussion, the team talked about how they were much more efficient with their tape usage with the second prototype as compared to the first prototype.

The third and final evaluation prompt was, "If you could do another redesign, how would you try to improve your solution?" Noelle had written about a design component unrelated to heat transfer, and the team spent three minutes discussing it. The student team then talked about copper wire. All four members of the team had written a statement about copper wire as an answer to the prompt. Dylan wrote, “I would of used copper wire like we did for the redesign.” The other three team members all wrote that they would use more copper wire; Sheldon and Noelle also specified a location, writing, “on the bottom,” and, “inside the prototype,” respectively. Their notebook answers seemed to imply that the students had scientific conceptions about why the copper wire was important. However, during the discussion, Noelle and Marie revealed their alternative conceptions about copper wire.

> Noelle: I feel like we should have lined it [copper wire] on the sides and on the top as well.
> Marie: That’s what I said, but somebody wouldn’t let me! *(Marie looks pointedly at Sheldon.)*
> Sheldon: You didn’t say that!
> Marie: Yeah, I did! I was like, why don’t we line the whole thing? But you were like, “No, let’s just do the bottom.”

When the student team was discussing possible redesign ideas during the decide (about whether a solution is successful) step of the first round of solution generation, Marie had proposed using copper wire on the bottom and the sides of the containers. At that time, Sheldon had explained that because copper wire was a conductor, they only needed it on the bottom of the container; he also had said, “Why would we put it up here [on the sides] where it’s not touching anything?” However, during this most recent discussion, Sheldon did not say anything about conduction to counter Marie and Noelle’s idea. It is possible that because two team members now disagreed with him, he lost confidence in his conceptions. Regardless, the two conversations indicate that Sheldon had scientific conceptions about copper wire since he only wanted to use it on the bottom of the container that was in contact with the heating pad. These scientific conceptions were that *conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas* and that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. However, Marie and Noelle’s idea to put copper wire on the sides and top of the container show that they did not have these scientific conceptions. They had the alternative conception that <u>copper wire transfers heat quickly regardless of context (i.e., no distinction between conduction and radiation)</u>.

4.2.3.2 Lesson 12: Communicating with the client.

During the final lesson of the *Ecuadorian Fishermen* unit, there were two main activities. First, the students individually wrote letters to the client about the problem and their recommended solution. During this activity, most of the members of the student team discussed several conceptions about heat transfer. Second, the students reflected about how their understandings changed during the engineering design process, specifically how their understanding of the problem changed and how their understanding of how to design a solution changed. However, the student team did not write much for either of these prompts, and none of them explicitly discussed conceptions about heat transfer. Therefore, the remainder of this section describes only the first activity.

Mr. Parker directed students to review the letter from the client that they had received in Lesson 1. At the end of the letter, there was a list of instructions about what information the students should communicate back to the client. Mr. Parker read these aloud, and then he projected them on the front screen as the prompt for the activity.

> In your letter, you should:
> - Review the problem
> - List criteria and constraints
> - Include a labeled diagram
> - Explain what the parts do
> - Use data and evidence from previous investigations to justify why your design was successful

Mr. Parker divided these prompts into three general categories: the problem, criteria, and constraints; the design solution including a diagram and explanation; and the justification including data and evidence. For each category, he led a brief whole class discussion reviewing the prompts of the category, and then he gave students time to write about those prompts in their letters to the client. In total, the students had most of one full class period, approximately 40 minutes, to work on their letters to the client. Because the students worked on the letters individually, they are described individually starting with Sheldon and Noelle, who had fairly detailed letters, and ending with Dylan and Marie, who had less complete letters.

Sheldon started his letter with a fairly accurate description of the engineering challenge, criteria, and constraints.

> The problem we were trying to solve, was making a solar oven container. We needed to make it to where it would work. The client was going to choose the cheapest one and the

> one that got the hottest in 10 minutes. We had to use the materials we were given. The criteria was to build a solar oven container that works. The constraint was the list of materials.

He then drew a top view, side view, and bottom view of the cooker container that described the materials used and their purpose. On the top view, he wrote “black felt to absorb heat,” and a “pipe cleaner for a handle” and drew an image to match. The statement about the black felt was based on the scientific conception that *dark colors absorb radiation/light energy,* though he used the word “heat” instead of “light.” For the side view, he wrote, “transparency sheet to let light in,” which is a version of the scientific conception that *clear materials transmit radiation/light energy*. For the bottom view, he wrote, “Al foil to absorb heat,” and “copper wire to absorb heat.” Although his use of the phrase “absorb heat” here could suggest that Sheldon was incorrectly using a radiation term in a conduction context, it is more likely that he was simply using “absorb heat” as a substitute for “conduct heat” given his earlier conceptions of copper wire conducting heat. The second scenario is more likely because Sheldon had consistently and correctly applied the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* to the design of the first and second cooker container prototypes. His overall justification was, “This design was successful because we used less materials and used materials that heat up quickly.” In general, this statement is a correct evaluation of the team’s second cooker container prototype, though it is not specific enough to determine which, if any, heat transfer conceptions Sheldon based it on.

Similar to Sheldon, Noelle began her letter with an accurate overview of the engineering challenge, criteria, and constraints.

> The problem was that they needed a solar oven to cook and hold fish while the fishermen were at the market to earn more money. Some goals that we needed to reach was to get the highest temperature in ten minutes. One constraint was we had to have the lowest cost possible. Also we were only issued certain materials.

She drew a top view and side view of the second cooker container prototype, labeling the top material of “Black felt,” side material of “Transparency sheets,” and bottom material of “copper wire.” (She did not label the aluminum foil that was also on the bottom of the container.) She then explained the parts and justified the design.

> Our temperature increased by 23ºC. The reason why we used those certain materials because Black felt is good at absorbing heat. The transparency sheets worked well on the sides because they are good at radiating heat. Also we used copper wire because it’s good

> at conducting heat. Our design was successful because we got a higher temp than we did the first time we tested it. Also we had a low cost at $10.00.

Noelle was the only team member to cite data about the second cooker container prototype, describing its temperature increase and cost. Similar to Sheldon, the statement about the black felt seemed to be based on the scientific conception that *dark colors absorb radiation/light energy*, though she used the word "heat" instead of "light." Also, her statement about the copper wire "conducting heat" was based on the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. However, it is less clear what she meant when she wrote that the transparency sheets "are good at radiating heat." It is clear that she made a connection between transparency sheets and radiation, but what that connection was, and therefore whether it was a scientific or alternative conception, is not clear.

Dylan did not write anything for the first 10 minutes of the activity. By the time she started writing about the problem, criteria, and constraints, Mr. Parker had moved on to the next section of the client letter, which was the design solution including a diagram and explanation. This meant that Dylan's letter to the client combined parts of the problem and solution, rather than describing the problem followed by the solution. She also included a drawing of the student team's second cooker container prototype, though she only labeled the top as "BF" (i.e., black felt) and bottom as "CW" (i.e., copper wire).

> The problem is that the fishermen do not have a good enough way to cook the fish in the solar ovens. A criteria that I thought of was to reach a certain temperature and I would do that by putting black felt on top because it absorbs light. A constraint that I was thinking of was trying out how less of materials we could use because I feel like adding a bunch of materials might be a reason why it's not a good temperature.

Dylan clearly demonstrated one scientific conception when she suggested, "putting black felt on top because it absorbs light." The conception demonstrated was that *dark colors absorb radiation/light energy*. She described that "adding a bunch of materials" might have negatively affected the temperature, but she did not provide enough information to link that statement to a scientific conception. An interesting note about Dylan's letter to the client is that she still seemed to have a misunderstanding about a criterion of the engineering challenge. For most of the unit, she consistently wrote that the goal was to reach a "certain temperature" or a "correct temperature," rather than to reach the highest temperature possible in 10 minutes. This is not an alternative conception in terms of science conceptions, but it does show that Dylan did not completely understand the goal of the engineering design.

Marie put little time and effort into her letter to the client. Her first draft contained a brief description of the challenge, one criterion, and some materials in the prototype.

> You asked us to build a small cooker container to fit in a solar oven for the fishermen. So that the fish could warm up or even cook. In our design we put all transparency sheets on the sides and put on the bottom copper wires.

After this text, she drew and labeled a container with a black felt top, transparency sheet sides, and copper wire and Al foil bottom. At this point, Marie stopped writing without having included any supporting statements for why the team used the materials that they did. The researcher noticed that she had not done this, and so she checked in on Marie.

Researcher:	So can you write, have you justified yet?
Marie:	What do you mean?
Researcher:	So this is the design. But then, can you explain, why did you choose each of these things?
Marie:	Oh

After this, Marie added to her letter, "I chose the transparency sheet because it gets to the highest." Before she finished her statement, Mr. Parker concluded class for that day. During the first part of the next day which was the last day of the unit, Mr. Parker gave students some time to complete their letters to the client; Marie did not even open her notebook. Thus, this partial statement was the last text she included in the letter. It is possible that she was referring to the results of the radiation lab or to the results of the first round of prototype testing, since transparency sheet objects had high temperature increases in both of those activities. However, without more information, it is difficult to tell what activities or conceptions she was referring to.

On the last day of class, Mr. Parker gave the students five minutes to talk about their letters to the client in their small groups. At first, the team sat silently. In an effort to start a conversation, the researcher asked the team, "So what did you guys have for justification? Why is your design awesome?" Sheldon, Noelle, and Dylan looked at their notebooks. Marie opened her notebook for the first time during class that day, read something, then closed it. Eventually, Noelle said, "A higher increase the second time than the first one," which started a discussion.

Marie:	I think what we did wrong the first time was we just made it really thick.
Noelle:	The thing I think we should have done the second time, though, was to add copper wire to the sides and top.

Marie: And less black felt.
Noelle: I don't think the black felt did very good too, yeah.
Marie: I think it just made it thicker and didn't make it work.
(The team discusses the costs of the two designs.)
Noelle: What did you put, Dylan?
Dylan: I thought that copper wire was really good on the bottom.
(The researcher asks Dylan to repeat what she said, and she does.)
Noelle: What do you think, Sheldon?
Sheldon: I put if I could change it, I would add more copper wire.
Noelle: Well, what do you think…? How did the, how was our thing successful?
Sheldon: We added the copper wire to the bottom with the aluminum foil.
Marie: We should just do the whole entire thing with copper wire.
Noelle: Yeah, we should have.
Marie: Just a whole bunch of copper wire, and then just like form it into a box or something.

During this discussion, the student team talked about two ideas. The first idea that Noelle and Marie discussed was that their first cooker container prototype was "really thick," in part due to having too much black felt. Noelle and Marie frequently discussed the first cooker container prototype being "too thick" during Lessons 10 and 11, so this idea was not a new one. Similar to their previous statements, they used the term "too thick" without explicitly connecting it to heat transfer conceptions, whether those conceptions were scientific or alternative. The second idea the team discussed was the use of the copper wire. Sheldon and Dylan agreed that copper wire worked really well on the bottom of the cooker container. Based on previous excerpts about copper wire on the bottom of the cooker container, this idea is probably based on the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. In contrast, Noelle and Marie said that they should make the entire container out of copper wire, including the bottom, sides, and top. This was an idea that Noelle initially suggested at the end of Lesson 11 when the team was asked what they would do if they could redesign again, and she and Marie brought it up again here. This idea to put copper everywhere is based on an alternative conception that <u>copper wire transfers heat quickly regardless of context (i.e., no distinction between conduction and radiation)</u>. In other words, Marie and Noelle did not understand that the copper would transfer heat differently when placed on the bottom of the container (where conduction was the primary form of heat transfer) than when used on the sides and top of the container (where radiation was the primary form of heat transfer). Similar to what happened when Noelle first talked about this idea during Lesson 11, Sheldon did say anything about conduction to counter Marie and Noelle's idea, though he did not say anything to support the idea either.

4.3 Heat, Thermal Energy, and Temperature Throughout the Unit

In addition to the conceptions that the student team used more explicitly throughout the unit, they also revealed some conceptions about heat transfer implicitly based on how they used certain terms such as "temperature," "thermal energy," and "heat." This section describes their use of these terms in both their spoken and written language. Note that this section only describes instances when the students used the terms in their words. Their speech and notebooks excerpts that were copied verbatim from information provided by Mr. Parker (e.g., notebook prompts, vocabulary definitions) were not included in this analysis.

For most terms related to temperature, the student team was consistent. The always used the word "temperature" as a property of a material or object. For example, they often stated that an object "has/had a higher/lower temperature," or that "the temperature [of an object] is a [certain number of] degrees." The student team also always used the term "degrees," or in this case "degrees Celsius," as a unit of measurement for temperature. In addition to quantitatively describing temperature, they also consistently used "hot," "hotter," "hottest," "cold," "colder," and "coldest" as words to qualitatively describe temperature. For example, they made statements about "hot air" and "cold air;" that an object "is hot," "is cold," or "feels coldest;" and that an object "gets hot." Once, they used the term "coolest" in this context, saying, "That's the coolest," about a piece of metal.

The one word related to temperature that was used in two different ways was the term "warm." In nine instances, the students used the word "warm" similar to "hot," as a qualitative descriptor of temperature. They said, "[an object] is warm," or "warm air." However, in eight instances, they used "warm" as the action "to warm up." In these instances, the word "warm" was used more synonymously with the term "heat." In sum, "warm" was used as a way to qualitatively describe the temperature of an object and as an action that happens to an object.

The student team used the term, "heat," 125 times during the unit when speaking or writing. The most common way that "heat" was used was "heat up," with 45 instances. This category included phrases such as, "to heat up," "will heat up," and "heats up." Here, students were using term "heat" as "a process of increasing temperature," which is fairly close to the scientific conception of heat.

The second most common category included various terms of verbs that acted on heat. They were phrased as, "[an object] *[term(s)]* heat" or "to *[term]* heat." These terms and their frequency of usage are listed in Table 4.8.

Table 4.8. *Uses of the word "heat" when described in the sense of "to [term] heat"*

Term/phrase	Number of instances
transfer heat	8
absorb heat	7
block the heat, block out heat	7
conduct heat	4
give heat	2
produce heat	2
radiate heat	2
keep the heat in	2
pass heat off to	2
add heat	1
bring the heat out	1
get the heat in	1
let in heat	1
put the heat down	1

One of the most common terms in this category is "to transfer heat," or [an object] "transfers heat" or "is transferring heat." This phrase, "transfer heat" or "transfer of heat," was used in several definitions and prompts in the unit. "Absorb heat" and "conduct heat" were not in any written prompts or definitions in the *Ecuadorian Fishermen* unit, but Mr. Parker said them occasionally when leading whole class discussions. The student team used the phrases, "block the heat," or "block heat out," only during Lesson 7, when they responded to the prompt, "Which materials will best block heat transfer via conduction (i.e., are insulators)?" Because these phrases were used in the unit or by Mr. Parker, it makes sense that students would continue to use them in their own words. Also, these phrases are commonly used in scientific texts, so although they might be seen to imply that heat is a substance, they are scientifically appropriate uses of "heat." The other phrases, such as "give heat" and "keep the heat in," are more mixed in terms of whether they are scientifically acceptable. However, it is worth noting that students used these phrases less often than the more scientifically acceptable phrases.

The third most common category included actions that "heat" did, which were phrased as "heat *[term(s)]*" or "heat will *[term]*." These terms and their frequency of usage are listed in Table 4.9.

Table 4.9. *Uses of the word "heat" when described in the sense of "heat [term(s)]"*

Term/phrase	Number of instances
heat (energy) transfers	7
heat travels	4
heat is going to come out	2
heat goes	2
heat escapes	1
heat will leave	1
heat will start there	1
heat is attracted to	1
heat absorbs	1

The phrases "heat transfers" and "heat energy transfers" were used in the *Ecuadorian Fishermen* unit and are generally accepted as appropriate terminology in the scientific community. Most of the other phrases in Table 4.9 seem to be versions of the idea that "heat moves" or "heat flows."

The remaining 19 instances of heat varied in in terms of both how students used the term and how scientifically acceptable that use was. Noelle twice spoke about the "heat pad," and Dylan referred to the heat lamps once as "the heat things," so in these instances, "heat" was used as part of an object name. The student team used the phrase "all the heat" four times. The last 12 instances of the use of "heat" are in Table 4.10.

Table 4.10. *Miscellaneous uses of the word "heat"*

Student	Term/phrase
Sheldon	[Because] we're learning about ice! No, I mean about heat transfer.
Dylan	The similarities is that they all do something with heat.
Marie	The metal chair felt colder because of the absorption of heat.
Sheldon	The heat conduction.
Noelle	Some melted faster because they are faster heat conductors.
Marie	Radiation is heat waves that transfer through space.
Sheldon	The way the Sun's heat gets to us.
Noelle	There are multiple causes of radiation like heat.
Marie	I would do transparency because…it had the most heated on there [data table].
Marie	[White felt] would be heat.
Marie	So [because] of the heat.
Noelle	So then this one would be a heat…

The instances near the beginning of Table 4.10 are more scientifically acceptable, either talking about the general topic of "heat" or using "heat" as to more explicitly describe another heat transfer term, such as "heat conduction." The instances nearer to the bottom of Table 4.10 are less scientifically sound, such as "[white felt] would be heat."

The final term analyzed was the term, "thermal energy." In *NGSS*, "thermal energy" is introduced as a concept at the middle school level, and thus the term was introduced in the *Ecuadorian Fishermen* unit along with "temperature" and "heat" in Lesson 2. During Lesson 2, students wrote a definition for "thermal energy" and were able to answer questions about thermal energy when comparing two objects. Also, Mr. Parker tried to use "thermal energy" repeatedly throughout the unit, not just Lesson 2. However, the student team only used "thermal energy" in their own words twice throughout the unit. When Noelle wrote a response to prompt during the convection activity, she initially wrote, "The process of heat transfer this represents is the process of thermal energy." Later, she changed her response to, "…the process of convection," which was the correct response. The second time that a student on the team used "thermal energy" was when Marie wrote a description of conduction during a review activity in Lesson 6. She wrote, "conduction is through how thermal energy," which was not even a complete thought. Even though the students were introduced to the term "thermal energy" as part of the unit, they only used it on their own twice, and neither time indicated an understanding of the term.

4.4 An Embedded Unit of the Case: Dylan

One of the main goals of this embedded case study was to identify students' heat transfer conceptions through their participation in an engineering design-based STEM integration curricular unit. These heat transfer conceptions were found by analyzing students' verbal communication during the unit, which included what they wrote in their engineering notebooks and what they said during small group and whole class discussions. Three members of the student team – Marie, Noelle, and Sheldon – consistently communicated in spoken and written formats. They revealed many scientific and alternative conceptions about heat throughout the course of the *Ecuadorian Fishermen* unit. However, it was much more challenging to interpret Dylan's conceptions because she rarely spoke, and she did not write responses to several prompts in her engineering notebook. This section describes Dylan's participation, and lack thereof, during the unit, in order to explain why there is less information about her heat transfer conceptions than those of her teammates.

Dylan spoke very little during the unit, and even when she did, the statements she made often did not reveal any information about her conceptions. She only participated in a whole class discussion once, and that was when Mr. Parker asked her to read the digital display on the infrared thermometer when he measured the temperature of various objects in the classroom during Lesson 3. Even in the small group discussions, she did not say much. When she did speak, her most common statements were one-word answers about whether she agreed or disagreed (i.e., "Yeah," "No," "Okay") or short phrases indicating uncertainty (i.e., "Umm…," "I don't know," "What?"). When directly asked a question by another member of the team or the researcher, Dylan always attempted to answer, though again the answers were frequently short phrases. Also, it was fairly common (i.e., about once per day) that one team member would ask Dylan to contribute, and before she could say anything, another team member would answer the question. After this interruption, sometimes Dylan was eventually able to answer the question, and other times she was not. When she did say an extended phrase without prompting, it was usually to ask a question, either checking with the team about what they had written or asking how to do a hands-on task that had been assigned to her. The times when she stated an extended phrase about heat transfer, such as the few times she talked about it being important to use copper wire on the bottom of the cooker container, were very rare compared to the other three members of the team.

Dylan also expressed fewer heat transfer conceptions than her teammates when comparing their engineering notebooks. However, she still completed the majority of the prompts. Of the 96 individual prompts Mr. Parker gave the students during the *Ecuadorian Fishermen* unit, Dylan completed responses to 75, partially completed 8, and did not respond to 13. (Each "prompt" varied in size, with some requiring a few word answers and other requiring a lot of information. For an example of a prompt that required a more extensive response, three of Dylan's eight partially completed prompts were her three individually generated design ideas; these were partially completed because she wrote materials but did not include drawings or justifications.) Dylan spent more time thinking before beginning to write than her teammates, and sometimes she needed help getting started. The most notable example of this occurred in Lesson 7 when Dylan did not write anything for the first 12 minutes of the activity and only started after the researcher helped her begin to think of a design idea. Even though she wrote responses to fewer prompts than her teammates, she still responded at least partially to 86% of the prompts, which meant that most of her evidence of heat transfer conceptions came from her written notebook responses instead of her spoken statements during small group discussions.

Although did Dylan not contribute much to the team in terms of heat transfer conceptions, she did participate. She attempted to answer any question that someone asked her, even though she was sometimes interrupted and her answers were often brief. If a team member directed her to do a hands-on task, such as measuring the temperature of the model agar fish or building a component of a cooker container prototype, she did so. Also, she asked questions if she was unsure about what they had asked her to do, attempting to make sure that the did the hands-on tasks correctly. Dylan also contributed several times by answering her teammates' logistical questions, answering questions about spelling, what they were supposed to currently be doing, or what they had done in the past. For example, after the winter break when the team wrote their letters to the client, Noelle struggled to remember what material the student team had used for the top of their second cooker container, and Dylan reminded her that they had used black felt. In sum, Dylan participated in the unit in some ways, but she did participate much in terms of communicating her conceptions about heat transfer.

4.5 Brief Summary of Results

The main portion of this chapter was a chronological, thick description of the case, including detailed information about the context, students' scientific and alternative conceptions, and supporting evidence from their spoken and written statements. Additionally, the chapter included an overview in which the heat transfer conceptions were shown by lesson (section 4.1), an analysis of students' semantic uses of heat transfer terms (section 4.3), and additional information about one student in the case (section 4.4). The more extensive summary of results, which is organized into four parts representing four components of the STEM Integration Framework, is explained in the next chapter. For each component of the STEM Integration Framework, the results are summarized and connected to literature.

CHAPTER 5. SUMMARY OF RESULTS AND DISCUSSION

In this section, I summarize the results which answer this study's research questions:

- During an engineering design-based STEM integration unit:
    - What scientific and alternative conceptions about heat transfer does a team of middle school students use?
    - How do engineering design, redesign, teamwork, and communication influence students' use of these conceptions?

I also relate these results to existing literature and how the results confirm, contradict, extend, and refine that literature.

This section is organized into four sub-sections which are aligned with the four components of the STEM Integration Framework (Moore, Stohlmann, et al., 2014) that are most important to the study. In the first sub-section, **standards-based science content**, the first research question is answered, and the heat transfer conceptions that the student team used are related to other heat transfer conceptions from pre-college science education and engineering education literature. The remaining three sub-sections contain summaries and discussions related to the second research question. In the **use engineering design practices to solve an engineering design challenge** sub-section, I describe how the steps of an engineering design process – including problem scoping and the initial round of solution generation – influenced students' use of heat transfer conceptions. The third sub-section, **at least one opportunity to learn from failure and redesign**, extends on the second, describing what happened in the second round of solution generation. The last sub-section, **develop teamwork and communication skills**, describes how practices of teamwork and communication influenced students' ability to use heat transfer conceptions. For the engineering design and redesign sub-sections, the results summary is presented first, followed by the related discussion. In the science content and teamwork and communication sub-sections, the results and discussion are presented for each idea within the sub-section. The last sub-section of the chapter is a brief summary of results across all four components, in terms of the answers to the research questions.

5.1 Standards-based Science Content: Summary of Results and Connection to Literature

This section focuses on answering the first research question about what scientific and alternative conceptions about heat transfer the students used during the *Ecuadorian Fishermen* unit. In particular, these conceptions are compared to common conceptions in the science education and engineering education literature.

For a few conceptions, the team in this study demonstrated scientific conceptions when the literature shows that students typically have alternative conceptions. For some conceptions, there was evidence that the students corrected their alternative conceptions as a result of participating in the unit. For other conceptions, the students seemed to already have scientific conceptions about certain ideas within heat transfer.

Based on how they used the terms throughout the unit, the student team distinguished between temperature and heat, which is not always true of middle school students (Schnittka & Bell, 2011). The student team used the word "temperature" to describe the property of an object or material, and they consistently used "degrees" and "degrees Celsius" as the unit of measurement for temperature. This conception of temperature as a measure of an intrinsic property of an object is scientific and is consistent with conceptions about temperature of adults (Carlton, 2000; Galili & Lehavi, 2006) and some students (Kesidou & Duit, 1993; Shayer & Wylam, 1981). Although the student team used the word "heat" in several different ways (see section 4.3), they most commonly used phrases such as "to heat up," "to transfer heat," and "heat transfers." These uses indicate that for the most part, the team thought of heat as a process of transfer or a process of increasing temperature, which is distinct from temperature as a property of objects. One note about this result is that, although it is clear that the student team thought of temperature as an intrinsic property, it was not possible to tell what they thought that property was other that the fact that it was related to hotness and coldness. Therefore, the students may have had the conception that temperature is a measure of the quantity or degree of heat in an object, which is an alternative conception expressed by other students (Kesidou & Duit, 1993; Shayer & Wylam, 1981) and adults (Carlton, 2000; Galili & Lehavi, 2006), but there was not explicit evidence of it.

As seen in the analysis in section 4.3, the majority of instances in which the student team used the word "heat" were phrased in a scientifically acceptable way. The most common phrase was "to heat up," which implies heat as a process of increasing temperature. Their next most commonly used phrases, "transfer heat," "absorb heat," "block heat," "conduct heat," and "heat transfers," were used in the *Ecuadorian Fishermen* prompts or by Mr. Parker when he explained concepts. Also, most of them are also phrases used in science education literature (Lewis & Linn, 1994) and NGSS (NGSS Lead States, 2013). There were some lesser-used phrases that the team used that implied they might have alternative conceptions about heat. For example, the phrase, "keep the heat in," implies that heat resides in the object, and the phrase, "heat goes" implies that heat is a substance that moves; both of these are categories of alternative conceptions about heat described by Wong, Chu, and Yap (2016). However, they used the term "heat" using scientifically acceptable phrasing much more often than phrasing that implied alternative conceptions. Additionally, the team never used the alternative conception of cold as a substance that moves (Clough & Driver, 1985; Erickson, 1979; Schnittka & Bell, 2011). They exclusively used "cold" as an adjective, for example, to say that something "is cold" or to describe "cold air."

Another interesting point about their use of the word heat is to compare it to the use of the term "thermal energy." Although the student team was able to identify which of two objects (of different size and temperature) likely had more thermal energy during Lesson 2, none of them ever said the term during the unit, and Marie and Noelle each only wrote the term once in their notebooks. (Both instances were incorrect.) Even though they were introduced to the term "thermal energy," Mr. Parker tried to use the term often, and it was used in notebook prompts and questions, the team exclusively used "heat" even when "thermal energy" would have been more scientific. The term was included in the *Ecuadorian Fishermen* curricular documents because it is part of the middle school level performance expectations of NGSS (NGSS Lead States, 2013), but the student team almost never used it. This result contributes additional evidence to an argument made by other researchers that using "heat" for both "heat" and "thermal energy" is more developmentally appropriate for middle school students (Arnold & Millar, 1994; Linn & Songer, 1991). Additionally, even experts tend to use "heat" when "thermal energy" would be more appropriate (e.g., "heat transfer" instead of "thermal energy transfer"; Bauman, 1992) , so it is not surprising that the student team used similar phrasings.

It is also interesting to note that the student team never used the phrase "heat rises," which is commonly used by students in other studies (Clough & Driver, 1985; Erickson, 1979; Schnittka & Bell, 2011). When they learned about convection in Lesson 2 and reviewed the concept in Lesson 6, they only ever spoke and wrote about "hot air" or "hot water" rising. They also used this scientific conception, that *hot fluids rise*, when creating both of their prototypes. In the first round of solution generation, Noelle pointed out to the team that, “Now that I realize it, won’t the heat escape when, since this [the top] isn’t closed?” after the team had created their first prototype, leading them to seal the prototype. In the second round of solution generation, the team decided against cutting a hole in the top felt piece since “the heat will leave.” Although these two instances are phrased “heat escape” and “heat will leave,” they indicate that the student team used the scientific conception that *hot fluids rise* and thus sealed both prototypes to prevent hot air from rising out of the prototypes.

One of the most obvious conceptions that the students improved upon during the unit was an alternative conception that the temperature of an object depends on the material it is made of and can be determined by touching the object. In other words, when asked about the perceived temperature of various objects that have equilibrized with an ambient temperature, pre-college students (Clough & Driver, 1985; Lewis & Linn, 1994; Paik et al., 2007; Shayer & Wylam, 1981) and nonscientist adults (Carlton, 2000; Lewis & Linn, 1994) often say that objects such as metal that feel colder are actually colder (i.e., have a lower temperature) than objects that feel warmer. During the *Ecuadorian Fishermen* unit, this conception was explicitly addressed during Lesson 2 when Mr. Parker asked students to feel metal and wood objects in the classroom and then used an infrared thermometer to measure them. At first, the students in the class expressed surprise that the two objects that felt different were actually the same temperature. Sheldon even questioned the accuracy of the thermometer, which is also what some adults do when presented with this cognitive conflict (Lewis & Linn, 1994). However, after watching a *Veritasium* video that explained the phenomenon and provided additional demonstrations, the students on the team learned that although the objects were at the same temperature, they felt different because they conducted heat away from their hands at different rates. Henceforth, several student team members repeatedly used this scientific conception that *materials at the same temperature can feel different because they transfer heat at different rates*. Not only that, but Sheldon also used this information to create a heuristic. He reasoned that if materials feel cold because they transfer heat more quickly away from a person’s hand, and if materials that transfer heat more quickly are conductors, then *a material that feels colder will transfer heat faster (i.e., is a better conductor)*. As a general rule of thumb, this is a fairly scientific heuristic. Sheldon then used this heuristic to identify better conducting materials during activities in Lessons 2 and 7. Schnittka and Bell (2011) discovered a similar result with the *Save the Penguins* curriculum, which also targeted the common alternative conception about how materials feel. After experiencing targeted demonstrations, some students in the study talked about the scientific conception that "conductors take thermal energy away from your body" (Schnittka & Bell, 2011, p. 1875). By targeting this alternative conception, students who participated in the *Ecuadorian Fishermen* and *Save the Penguin* design-based curricula learned that how materials feel is an indication of the rate of heat transfer through the material, not the actual temperature of the material.

Another conception that the student team used during the unit was the idea that *the direction of heat transfer is from hotter objects (i.e., objects with higher temperatures) to colder objects (i.e., objects with lower temperatures)*. During Lesson 2, they said and wrote about this scientific conception multiple times when they described heat transferring from their hands to materials in the classroom, including ice cubes, and heat transferring from the room temperature blocks to ice cubes during the conduction lab. The student team used similar conceptions to students who participated in the *Save the Penguins* curriculum, who understood that heat transfers from higher temperatures to lower temperatures, and that also means heat transfers from room temperature to colder objects (Schnittka & Bell, 2011).

Although the team seemed to have mostly scientific conceptions about heat, temperature, the direction of heat transfer, how one's hand feels the rate of heat transfer and not the temperature, and convection, there was a greater mix of scientific and alternative conceptions about the heat transfer processes of conduction and radiation. In some instances, the student team stated the scientific conception, but their use of the conception when designing solutions indicated an incomplete understanding of the conception. In other instances, the team created entirely new alternative conceptions that combined aspects of conduction and radiation.

The student team's views of conductors and insulators changed from scientific to alternative to scientific throughout the unit. By the end of Lesson 3, all four members of the team had used the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)* at least once. When they started the thermal properties of materials activity in Lesson 7, they initially used this conception, discussing whether they should write "metals" or a specific metal (e.g., steel, copper) as a material that is a good conductor. However, they then noticed the data table for the radiation lab and used those data to create two alternative conception, that <u>white felt is a good conductor because it had the highest temperature increase (during the radiation lab)</u> and that <u>aluminum foil is a good insulator because</u>

it had the lowest temperature increase (during the radiation lab). In their individual designs, Sheldon and Noelle used the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, wood (insulators)* to justify using aluminum foil on the bottom of their cooker containers where the heating pad was located, and they decided to use this design element for the team prototype. In contrast, Marie did not use conceptions about conduction for most of the first round of solution generation. During the second round of solution generation, the team used aluminum foil and copper wire on the bottom of their prototype, which is again based on the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. However, when asked what they would do for a third prototype, Marie and Noelle wanted to make an entire box out of copper wire (bottom, sides, and top), while Sheldon and Dylan still wanted to keep it on the bottom. In other words, although all four team members seemed to understand that *heat transfers more quickly through metals (conductors) than through plastic, paper, wood (insulators),* they differed in whether they understood how conduction worked in the cooker container and solar oven. Sheldon and Dylan seemed to understand the scientific conception that *conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas* because they wanted to use metal, a conductor, at the bottom of the container that would touch the heating pad. In contrast, Marie and Noelle seemed to use the alternative conception that copper wire transfers heat quickly regardless of context (i.e., no distinction between conduction and radiation).

Compared to students in other studies (Lewis & Linn, 1994; Paik et al., 2007), the team had more scientific conceptions about conductors. In addition to using the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, wood (insulators),* they also figured out the scientific conception that *more layers of material (i.e., thicker) are insulating because heat transfer via conduction is more difficult* when troubleshooting what went wrong with their first prototype. However, when attempting to apply the scientific conception about conductors to a design solution, two of the students demonstrated a scientific conception about conduction, and the other two used an alternative conception that implied that they were confused about the heat transfer processes of conduction and radiation.

The student team had mostly scientific conceptions about radiation, with one major exception, though they struggled to apply those conceptions scientifically to the design challenge. During Lessons 4 and 5, the student team used several scientific conceptions: *radiation is the* *transfer of heat across space in the form of light waves; when a material absorbs radiation/light waves, the temperature of the material increases; when a material reflects radiation/light waves, the light waves bounce off the material; when a material transmits radiation/light waves, the light waves pass through the material; dark colors absorb radiation/light energy than light colors; metals reflect radiation/light energy*; and *clear materials transmit radiation/light energy*. However, the radiation lab yielded data that conflicted with these scientific conceptions. The temperature inside of the cup covered in white felt increased more than the temperature inside of the cup covered in black felt, and the other two dark and light materials (construction paper) had the same temperature increase. Therefore, the students experienced a conflict between the scientific conception they thought they knew, that *dark colors absorb radiation/light energy better than light colors*, and the interpretation of the data, which said that *the white felt had the largest temperature increase in the radiation lab*. When students designed their first prototype, they used black felt on the interior because *dark colors absorb radiation/light energy*, and a white felt top with a small transparency sheet window because *the white felt and transparency sheet had the largest temperature increases in the radiation lab*. However, it was not until the container was built that they realized how little radiation would actually reach the black felt, since most of the top was white felt. Additionally, after Noelle proposed putting aluminum foil on the exterior sides of the container, Marie justified the choice with the scientific conception that *metals reflect radiation/light energy*. However, no one on the team realized that radiation would reflect away from the container. For the second design, the team used the conception that *dark colors absorb radiation/light energy* to justify their top of black felt, and they used transparency sheet sides because *the cooker container with transparency sheet top and sides had the largest temperature increase during prototype testing*. (Sheldon also consistently used the scientific conception that *clear materials transmit radiation/light energy* during solution generation.) Although the team used many scientific conceptions for both designs, they applied them much more correctly to the second prototype, resulting in a better performing prototype.

In using the scientific conception that *radiation is the transfer of heat across space in the form of light waves*, the student team recognized the connection between light and radiation; this contrasts with other students' conception that light and radiation are different (Neumann & Hopf, 2012). They also used the scientific conception that *dark colors absorb radiation/light energy*, which is different from the *Save the Penguins*' students' use of the alternative conception that dark object attract heat (Schnittka & Bell, 2011). (There was one instance in a whole class discussion when Sheldon used the term "attract heat" to describe darker objects, but Mr. Parker corrected it.) The students in both *Save the Penguins* and *Ecuadorian Fishermen* used light colored materials, but even though *light colored materials reflect radiation/light energy*, the student team was justified because unexpectedly, *the white felt had the largest temperature increase in the radiation lab*. Both groups of students also used the scientific conception that *metals reflect radiation/light energy*, but the student team in this study applied the conception poorly and light was reflected away from their container, which was supposed to maximize thermal energy transfer. One more interesting event happened with metals. When the team made predictions for the radiation lab, which occurred the day after the conduction lab, the student team predicted that because metals conduct heat, they will also absorb light. In other words, they based their prediction on the alternative conception that aluminum foil will heat up (in the radiation lab) because it is metal (and thus conducts heat). Using similar reasoning, other students have said that because metals reflect light, they also will reflect heat and not conduct it (Paik et al., 2007).

Finally, there were several alternative conceptions used by the student team that were not found in literature. First, there was a set of unique alternative conceptions that mostly occurred during the initial solution generation stage, and they fall within the broad category of being created as the student team combined various ideas and vocabulary about conduction and radiation to create one set of rules about how well materials transfer heat. Four of them have already been mentioned in section 5.4: white felt is a good conductor because it had the highest temperature increase (during the radiation lab), aluminum foil is a good insulator because it had the lowest temperature increase (during the radiation lab)., copper wire transfers heat quickly regardless of context (i.e., no distinction between conduction and radiation), and aluminum foil will heat up (in the radiation lab) because it is metal (and thus conducts heat). The team, at this point led by Noelle, also expressed three other alternative conceptions when filling out their evidence-based reasoning graphic in Lesson 8: the foil conducts the light, the black and white felt absorb the light that the foil conducts, and all the heat and light that is radiating to the foil and felt will absorb and conduct to the fish. Although these statements have portions that scientific ideas about conduction or radiation, each statement as a whole shows a confusion between conduction and radiation. This result is in contrast to students from the *Save the Penguins* unit, who demonstrated a basic understanding of and distinction between radiation and insulation when designing solutions for their engineering challenge (Schnittka & Bell, 2011). Those students demonstrated an understanding of which materials reflect and also which materials insulate. Also, the students were able to apply radiation and insulation conceptions to the context by putting reflective materials on the bottom of their prototypes to reflect radiation from black floor, using light colors and metals to reflect radiation away from the prototype, minimizing conduction by raising the dwellings off of the floor of the test oven. Although the two design contexts were similar, the student team in this study experienced much more confusion about different process of heat transfer.

Another set of unique alternative conceptions occurred when the student team attempted to justify their use of wood craft sticks. In addition to justifying their use of wood in their prototype because it is sturdy, the team also used the alternative conceptions that <u>wood absorbs radiation/light energy</u> and <u>wood is a good conductor</u>. One possible explanation for the former alternative conception is that student interpretation of laboratory results led to alternative conceptions of heat transfer. During the *Ecuadorian Fishermen* radiation lab, the wood sticks had the second lowest temperature increase. However, because the student team collected data for the material with the lowest temperature increase, it is possible that Noelle interpreted any other material to be "good at absorbing." In other words, because the wood was not worst at absorbing radiation, it was good at absorbing radiation. Lewis et al. (1993) had a similar result in that students' incorrect interpretation of laboratory results resulted in alternative conceptions about the heat transfer properties of materials. It is less clear how the latter of these alternative conceptions emerged in the student team especially since its opposite is true (i.e., wood is a good insulator). One possibility is that Marie heard Noelle use the alternative conception that <u>wood absorbs radiation/light energy</u>, and since Marie had difficulty distinguishing between conduction and radiation, Marie re-interpreted Noelle's statement to mean <u>wood is a good conductor</u>. Another possibility is that Marie mis-remembered the results of the conduction lab from Lesson 3, where the team's materials to test were a piece of wood and a piece of brass. The team had already experienced confusing about the conduction lab during Lesson 7, though at that time, it was Marie who reminded Noelle that "wood blocked out the heat" (i.e., was an insulator). Regardless of how the student team came to use the alternative conception that <u>wood is a good conductor</u>, this conception contrasts with the *Save the Penguins* unit, in which the students used the scientific conception that wood is a good insulator (Schnittka & Bell, 2011).

In sum, the student team used a mix of scientific and alternative conceptions during the engineering design-based STEM integration unit. For some topics (e.g., heat, temperature) students already had or learned the scientific conceptions as a result of the unit. For other topics (e.g., conduction, radiation), students used some scientific conceptions correctly when designing, some scientific conceptions incorrectly or incompletely when designing, and some alternative conceptions. This result is consistent with other studies about heat transfer; sometimes students use terms inconsistently (Lewis & Linn, 1994), and other times students seem to understand because they can use scientific-sounding phrases and vocabulary, but then they struggle to apply scientific conceptions when explaining similar ideas in novel contexts (Clough & Driver, 1985). Although the team struggled, they ultimately used more scientific conceptions than alternative conceptions throughout the unit.

5.2 Use Engineering Design Practices to Solve an Engineering Design Challenge

This section focuses on answering part of the second research question, specifically how engineering design influenced students' use of heat transfer conceptions as they participated in an engineering design-based STEM integration unit.

5.2.1 Summary of Results about Engineering Design

During the problem scoping stage, which included the engineering design process steps define (the problem) and learn (about the problem), the student team demonstrated mostly scientific conceptions. When students defined (the problem) in Lesson 1, they set themselves up for learning about heat transfer. When they generated questions to ask the client, the student team thought about what temperature, or how hot, the container needed to be. For one of the criteria, they spoke and wrote about "warming up" the fish. When they thought about what they might need to learn, they spoke and wrote about what temperature the oven heats up to and what materials heat up faster. Through these instances, the student team demonstrated that they understood that they needed to learn about heat transfer concepts in order to create a successful solution to the engineering challenge. In this way, Lesson 1 had successfully prepared them for the learn (about the problem) step of an engineering design process.

For Lessons 2-5 during the learn (about the problem) step of an engineering design process, the student team primarily used scientific conceptions about heat transfer. These scientific conceptions, which can be seen in Table 4.1, were related to the science concepts that were the focus of each lesson. In Lesson 2, they used scientific conceptions about temperature, thermal energy, the direction of heat transfer, and convection. Examples of scientific conceptions about heat transfer used in this lesson were *particles move faster when the temperature increases, the direction of heat transfer is from hotter objects (i.e., objects with higher temperatures) to colder objects (i.e., objects with lower temperatures),* and *hot fluids rise*. In Lesson 3, they used scientific conceptions about the direction of heat transfer, conduction, and thermal properties related to conduction (i.e., which materials are conductors vs. insulators). Main scientific ideas used by students in Lesson 3 were that *materials at the same temperature can feel different because they transfer heat at different rates*, *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators),* and *conduction is the transfer of heat through a solid or from a solid to another solid, liquid, or gas*. In Lessons 4 and 5, they used scientific conceptions about radiation and thermal properties related to radiation (i.e., which materials absorb, reflect, or transmit radiation/light energy). Examples of scientific conceptions used by students were *radiation is the transfer of heat across space in the form of light waves*, *when a material absorbs radiation/light waves the temperature of the material increases*, and *clear materials transmit radiation/light energy*. In sum, when each lesson focused on one or two main concepts about heat transfer, the student team mostly spoke and wrote about scientific heat transfer conceptions.

There was one main type of situation in which students used alternative conceptions during Lessons 2-5. Several of the activities during the science-focused lessons were predict-observe-explain activities, and students sometimes used alternative conceptions when they attempted to predict the outcome of an activity. For example, before the radiation lab, Noelle and Dylan wrote that they predicted that <u>aluminum foil will absorb radiation</u>, and during the discussion after the lab, Marie, Noelle, and Sheldon said that they had thought that <u>aluminum foil will heat up (in the radiation lab) because it is metal (and thus conducts heat)</u>. They had learned about metals being good heat conductors during the previous lesson, so the prediction that aluminum foil would absorb heat made sense. However, during the radiation lesson, the temperature inside the cup that was covered in aluminum foil increased very little, and the team learned the scientific conception that *metals reflect radiation/light energy*, which they all wrote in their engineering notebooks. In this type of situation, the students sometimes used alternative conceptions in their predictions, but they usually used scientific conceptions in their explanations after the demonstration or lab.

The results of the radiation lab also presented a unique conflict that the student engaged with during Lessons 4-5 and in subsequent lessons. The students generally understood that *dark colors absorb radiation/light energy better than light colors*. However, during the radiation lab, the temperature inside of the cup covered with white felt increased more than the temperature inside of the cup covered with black felt, and the temperature increases of the white and black construction paper cups were the same. Thus, the students were able to justify the ideas that dark colors absorb radiation, based on the scientific conception, and that light colors absorb radiation, based on the results of the radiation lab.

After using primarily scientific conceptions about heat transfer when the heat transfer concepts were presented individually during Lessons 2-5, the student team began using many more alternative conceptions when they needed to consider all three processes of heat transfer at the same time. This began in Lesson 6, the last lesson of the learn (about the problem) step, and continued through for much of the first round of the solution generation stage (i.e., Lessons 7-10). During the decide (about whether the solution was successful) step of Lesson 10, the students also answered prompts related to redesign. The students' written and spoken responses to these redesign prompts are discussed in the next sub-section; this sub-section only contains information about the students' individual ideas and the team's first cooker container prototype.

In Lesson 6 and the first part of Lesson 7, the students were meant to review the three processes of heat transfer and apply them to the context of the engineering design challenge, namely by thinking about how the three methods of heat transfer occurred in the solar oven and what were the thermal properties of the materials available for the prototype. However, for both of these activities, the members of the student team became confused about the different processes of heat transfer, and they were not able to finish the activities in the time allotted. When analyzing the solar oven in Lesson 6, they spent most of their time trying to remember what convection was, so they did not have time to talk about how conduction or radiation would occur in the classroom solar oven. When analyzing the materials available in Lesson 7, they quickly confused radiation thermal properties and conduction thermal properties when they used results from the radiation lab to answer question about which materials would be better conductors or insulators. They answered the first two questions about conductors and insulators with the alternative conceptions that white felt is a good conductor because it had the highest temperature increase (during the radiation lab) and that aluminum foil is a good insulator because it had the lowest temperature increase (during the radiation lab, respectively. Because of their confusion, they did not finish the rest of the activity in the time remaining, which were questions about which materials absorb, reflect, and transmit radiation. During these review and application activities, they used some scientific conceptions, but their alternative conceptions and inability to finish the activities were more dominant.

During most of the initial solution generation stage (i.e., Lessons 7-10), the students demonstrated a mix of scientific and alternative conceptions. Additionally, there was another layer of potential confusion that occurred when students attempted to apply their conceptions about heat transfer to the design of a cooker container prototype. These scientific and alternative conceptions about heat transfer combined with correct or incorrect applications to the design led to five main situations during the initial solution generation phase.

First, in a few cases, the students used scientific conceptions and correctly applied them to the design of the cooker container prototype. In their individual design ideas, Sheldon and Noelle both used aluminum foil on the bottom of their cooker container designs, and they agreed to use an aluminum foil bottom for the team cooker container design. They agreed to do so because *aluminum foil is a good conductor*, i.e., *heat transfers more quickly through metals (conductors) than plastic, paper, or wood insulators)*. The team also used mostly white felt or transparency sheet as the material for the top of their designs when they generated individual design ideas, and for their group design, they agreed to use white felt with a transparency sheet window for the top. They justified these choices for the top materials with the conception that *white felt and transparency sheet had the largest temperature increases during the radiation lab*. (As stated earlier, this idea is not a typical scientific conception, but it was a correct analysis of the radiation lab data.) Sheldon also justified the choice of the transparency sheet with the scientific conception that *clear materials transmit radiation/light energy*. For a few instances, the student team members correctly applied scientific conceptions to their individual and team designs.

Second, the team used scientific conceptions about heat transfer but applied them incorrectly, or in an unscientific manner. After Noelle proposed adding aluminum foil to the exterior sides of the cooker container, Marie supported this idea because "It [aluminum foil reflects light, and it makes it hotter." During her individual design ideas and the team design, Marie seemed to understand that *metals reflect radiation/light energy*. However, she was not able to correctly connect this scientific conception to the cooker container design; she did not realize that by putting a reflective material on the outside of the container, the radiation would be reflected away from the container. Another scientific conception that mostly Marie said and wrote was that *dark colors absorb radiation/light energy*. In all three of her individual designs, Marie included black felt as an interior material (i.e., on the walls and/or bottom), and the team agreed to put black felt on the interior walls of their first cooker container prototype. In two of Marie's individual designs, the top of the container was either made up transparency sheet or open, which meant that radiation could reach the black felt, so this was a fairly correct application of the scientific conception. However, in the team design, they had agreed to put a top of mostly white felt (with a small transparency sheet window) on the cooker container, which meant that much less radiation would even reach the interior black felt. Marie understood that *dark colors absorb radiation/light energy*, but it was not until the first cooker container prototype was fully constructed that she realized how little radiation would actually reach the black felt interior, saying, "I feel like we should have made the hole [transparency sheet window] bigger…so more light can get into it." In some instances, the team could use scientific conceptions, but they struggled to apply them correctly to components of the design.

Third, the team applied some alternative conceptions during the initial round of solution generation. In their individual design plans, Noelle and Marie had both used wood on the bottom and/or sides of their cooker containers, and during the team design plan, the student team agreed to use wood sticks for the walls of the first cooker container prototype. Usually, the team justified their choice of wood sticks because they would make the container sturdier, which is an adequate justification given the structural properties of wood sticks. However, when the team members also tried to justify this choice using thermal properties of wood, they used alternative conceptions. Noelle repeatedly used the alternative conception that <u>wood absorbs radiation/light energy</u>, and Marie then said that <u>wood is a good conductor</u>. When attempting to justify their choice of wood sticks for the sides of the cooker container, Marie and Noelle both used these alternative conceptions about the thermal properties of wood sticks. The team also used a set of alternative conceptions that fell within the general category of combining various ideas and vocabulary about conduction and radiation to create one set of rules about how well materials transfer heat. When generating individual ideas during Lesson 7, Sheldon used the alternative conception that <u>radiation will heat aluminum foil up faster</u>, basing this idea on the fact that aluminum foil is a metal and metals are good conductors. During Lesson 9, Marie said that white felt is a good conductor, basing this statement on the results of the radiation lab. On the team's evidence-based reasoning graphic, Noelle wrote three statements that that fell into this category: "The foil conducts the light," "The black and white felt absorb the light that the foil conducts," and "All the heat and light that is radiating to the foil and felt will absorb and conduct to the fish." This set of alternative conceptions contained scientific vocabulary, but on the whole seemed to confuse conduction and radiation.

Fourth, there was at least one instance where a team member either purposefully ignored or forgot about an aspect of the engineering challenge. For all of Lessons 7-8, Marie did not write or say anything about conduction, conductors, and insulators. She only wrote and spoke about radiation, materials "absorbing light," and materials "reflecting light" in her individual design ideas and when speaking with the team about their team design idea. It is possible that she purposefully ignored conduction because she thought that the effects of radiation in the solar oven would be far more important; however, she did not explicitly make this statement when speaking or writing. Therefore, it is likely that she forgot about conduction as a concept and that conduction would occur near the bottom of the container (where the container was in contact with a heating pad). Here, Marie did not use any heat transfer conceptions related to conduction, whether they were scientific or alternative.

Fifth, there were two design elements that the team agreed upon and were based on scientific conceptions, but only one explicit mention of the conception occurred. First, the entire team agreed to not only have a lid on their cooker container, but also that the lid should be sealed to the rest of the container. Additionally, when Sheldon measured the fish's final temperature in Lesson 10, he expressed regret that he had completely opened the lid before measuring the fish rather than only partially opening the lid. These actions imply that the team was correctly applying the scientific conception that *hot fluids rise*, since they wanted to prevent hot air rising out of their cooker container prototype. However, the only explicit mention of heat as related to this conception was during Lesson 9 when Noelle said, "Now that I realize it, won't the heat escape when, since this [the top] isn't closed?" during Lesson 9. Second, once the cooker container prototype was constructed in Lesson 9 and then tested in Lesson 10, Marie and Noelle frequently stated that it did not perform well because it was "too thick." However, during the initial solution generation phase, they only once explicitly related this idea of thickness to an underlying scientific conception. When they listed off all of the layers on the sides of the cooker container, Noelle said, "So it took too long to conduct." She may have meant "conduct" in a general sense, as a broad term for any method of heat transfer. However, she may have been basing this statement on the scientific conception that *more layers of materials (i.e., thicker) are insulating because heat transfer via conduction is more difficult*. Either way, she and Marie both understood that thickness was associated with poor heat transfer.

It is important to note that the five categories above are primarily based on the statements made by Marie, Noelle, and Sheldon. During the first round of solution generation, Dylan did not contribute any heat transfer conceptions during team discussions, other than to occasionally respond, "Yeah," to another teammate's statement. Also, it was difficult to determine her conceptions about heat transfer from her engineering notebook since she did not provide any indications of specific conceptions in the statement she wrote during this stage of engineering design. During Lesson 7, the researcher spoke with her extensively before she began to generate individual design ideas (see section 4.2.2.1). During these conversations, Dylan made a few statements that may have been based on scientific conceptions, but she also made many statements that seemed to be alternative conceptions. Therefore, it was difficult to determine if she was actually using any scientific conceptions, or if she was simply guessing materials until she got it "right" (i.e., the researcher approved). Because it was so difficult to determine what heat transfer conceptions, if any, Dylan used during the initial solution generation stage, most of the results summary in this sub-section were analyzed based on the other team members' communication.

In summary, the student team initially used mostly scientific conceptions during the problem scoping stage. During Lesson 1: defining (the problem), they understood why it was important for them to learn about heat transfer in order to solve the engineering challenge. For most of the learn (about the problem) lessons, in which each set of heat transfer concepts was presented individually, students demonstrated scientific conceptions about heat transfer. However, when students had to combine the conceptions about the different processes of heat transfer – conduction, convection, and radiation – they became confused and began to intermix vocabulary and ideas from the different processes. This confusion carried over into the first round of solution generation. Students used a mix of scientific conceptions and alternative conceptions, and they did not always correctly apply their scientific heat transfer conceptions to certain design elements. This led them to create a poor cooker container prototype, which had a temperature increase (14°C) less than a fish without a cooker container (16°C).

5.2.2 Connections to Other Literature about Engineering Design

One important finding is that the student team used heat transfer conceptions in every step of an engineering design process (see Table 4.1; Moore, Glancy, et al., 2014), and they used the most conceptions during three of the steps: learn/background, plan, and decide. During the define/problem step, the team happened to use one scientific conception based on their previous experiences, which was that *dark colors absorb radiation/light energy better than light colors*. However, they mostly used this step to learn about the engineering problem and challenge and why it was important for them to learn more about heat transfer. During the learn/background step, the students used many heat transfer conceptions. For the first few lessons of the learn/background step, the team used mostly scientific conceptions about heat transfer, but they began to use a larger mix of scientific and alternative conceptions when they had to think about the three processes of heat transfer in the same context. In the plan step, the team continued to use many heat transfer conceptions as they attempted to apply them to designing a cooker container prototype, though they used a mix of scientific and alternative conceptions. The student team used a few heat transfer conceptions during the try/implement step as they built their first prototype, mostly to justify their design choices to each other and to the researcher. However, they also used heat transfer conceptions to make a few adjustments to their design plan as they enacted it into a three-dimensional prototype, such as sealing the top with tape so that hot air would not escape. The team used very few heat transfer conceptions during the test step, and the few they discussed were the start of their evaluation conversation. This result, that students used few science conceptions when testing their design, was similar to another study that found no evidence of students applying science ideas when testing their ideas (Purzer et al., 2015). Finally, the team used many heat transfer conceptions, some scientific and some alternative, during the decide/evaluate step as they attempted to reason through why their first prototype did not perform well and why other teams' prototypes did. Even though this student team struggled in the sense that they used a mix of alternative and scientific conceptions when designing and also their first prototype did not perform well in the solar oven test, they still used many heat transfer conceptions in the problem scoping and solution generation stages.

While participating in the *Ecuadorian Fishermen* unit, the student team needed to use the science content knowledge that was the focus of the unit – heat transfer – in order to design a solution to the engineering challenge. While this is not true of all design-based curricula (Roehrig et al., 2012; Siverling et al., 2017), it was clearly true for the *Ecuadorian Fishermen* unit since the students needed to use heat transfer conceptions in order to meet one of the main criteria of the design challenge, which was to increase the temperature of a fish placed inside of their cooker container prototypes as much as possible in 10 minutes. Other studies have shown that some students focus more on financial feasibility (Guzey & Aranda, 2017) or aesthetic appeal (Barnett, 2005) than the science content, which tends to result in poor solutions. In contrast, the student team in this study considered cost but only after using science content to choose materials, and they rarely mentioned aesthetics. Additionally, the student team created a functional prototype by applying heat transfer conceptions, which is in contrast to students in other design-based activities that focused on creating representational models of real-world solutions instead of functional prototypes (Hmelo et al., 2000). Similar to other students in other studies, one of the ways in which the student team used science conceptions was to justify their design ideas and decisions (Mathis et al., 2018; Siverling et al., submitted). The student team discussed and wrote about other topics during the first round of solution generation, but they used many heat transfer conceptions also.

Although the student team in this study used many heat transfer conceptions during the first round of solution generation, they used both scientific and alternative conceptions. This result is similar to several other studies which have found that during engineering design, students use both scientific and alternative conceptions (Mathis et al., 2018; Schnittka & Bell, 2011; Wendell & Lee, 2010). One particularly impactful alternative conception for the student team was that they struggled to distinguish between thermal properties of materials in conduction versus the thermal properties of materials in radiation. This is different from another design-based unit about heat transfer, in which students used scientific conceptions about materials that reflect radiation and materials that are good insulators (Schnittka & Bell, 2011). Another level of difficulty for the student team was applying the heat transfer conceptions to the design. For some design elements, they correctly applied scientific conceptions, though they were explicit about their use of some scientific conceptions, and their use of other scientific conceptions was more implicit. For other design elements, they incorrectly or incompletely applied scientific conceptions, leading to poor design elements. Fortus et al. (2004) found a similar result, which was that a student team in their study applied scientific conceptions about insulation to a few design elements, but other design elements showed a lack of science concept application. Finally, the student team in this study also applied a few alternative conceptions to design elements. In sum, when students participate in design-based units, they sometimes apply scientific and alternative conceptions when solving an engineering design challenge, and sometimes they also create design elements that are not based on science conceptions.

5.3 At Least One Opportunity to Learn from Failure and Redesign

This section focuses on answering part of the second research question, specifically how learning from failure and redesign influenced students' use of heat transfer conceptions as they participated in an engineering design-based STEM integration unit.

5.3.1 Summary of Results about Redesign

The opportunity to learn from the failure of their first cooker container prototype and redesign, or complete a second round of the solution generation stage, noticeably influenced the student team's conceptions about heat transfer and their ability to apply them to a design. For the purposes of this sub-section, redesign began during the decide (about whether the solution is successful) step of the first round of solution generation. Because of the prompts given in this step during Lesson 10, the students began to think about what changes they would make to their design and why they would make them before they officially started to redesign in Lesson 11. This sub-section also continues through Lesson 12: Communication with the Client, when students wrote letters to the client recommending one of their solutions. During these activities, the student team worked through most of their alternative conceptions to produce a much improved second cooker container prototype that was based on scientific conceptions about heat transfer.

There were several scientific conceptions that the team was able to clarify and apply correctly during the second round of solution generation. Marie again proposed using black felt because "black felt absorbs more heat," which is based on the scientific conception that *dark colors absorb radiation/light energy*. This time, however, she proposed using the black felt for the top of the container, where it would be exposed to radiation, which is in contrast to the first design, where very little radiation reached the black felt. Sheldon, Noelle, and Dylan not only agreed with her, but they also used that justification, "black felt absorbs heat/light," in their letters to the client in Lesson 12. The team also continued to discuss how their first container was "too thick" and that they needed to avoid thickness for the second prototype. However, during the second round of solution generation, Mr. Parker talked to the team about this, helping them make a better, more explicit connection between thickness and insulation. For example, when talking about the second prototype as compared to the first, Sheldon said, "It's not as thick so it doesn't, it wasn't as insulated." Although the team hinted at this scientific conception during the first round of solution generation, during the second round they were more explicit that *more layers of materials (i.e., thicker) are insulating because heat transfer via conduction is more difficult*. They then correctly applying this conception to their second design by using one or two layers in each design element.

The team agreed upon one of the design elements, to cut a hole in the top of the cooker container, but only explicitly connected it to a scientific conception once throughout redesign. During Lesson 11, Noelle and Marie considered whether they should cut a hole in the top of the second cooker container so there was a place to put the temperature probe in. However, Noelle and Sheldon ultimately decided against it, since "the heat will leave." Similar to the first prototype, here the student team was implicitly applying the scientific conception that *hot fluids rise*, since they made sure that the design was sealed so that hot air could not escape. However, this conception was mostly implied, only explicitly stated or written about once.

During the second round of solution generation, the team discarded a previously-used alternative conception, though they did not do so for scientific reasons. As the team discussed possible design elements in Lesson 11, Marie said that, "wood is a good conductor." Sheldon responded, "So then let's put the wood only on the bottom, not on the sides also." During this instance and another instance that occurred later in Lesson 11, Sheldon also used the alternative conception that wood is a good conductor. When the student team first created a list of materials for the second design, they included some wooden sticks for the bottom of the container. Later in Lesson 11, the student team decided against using wooden sticks on the bottom, which was the appropriate decision based on scientific heat transfer conceptions. However, it was clear that they did not use scientific conceptions make this decision. Instead, they decided that wood might catch fire and burn, that wood is too expensive, and that the container would be sturdy enough without the wood sticks. In sum, the second cooker container prototype ultimately did not have wooden sticks in it, but the team decided against them due to reasons other than scientific conceptions about heat transfer.

There were two other main design elements that the team discussed, but whether they used scientific or alternative conceptions depended on the team member. First, the student team agreed to use transparency sheets for the sides of their second cooker container prototype. They agreed about this design element based on data from the first round of testing prototypes, that *the cooker container with the transparency sheet top and sides had the largest temperature increase during prototype testing*. In this sense, they all interpreted data correctly. However, when they explained their choice of transparency sheet further in their letters to the client, they showed mixed conceptions. Sheldon used the scientific conception that *clear materials transmit radiation/light energy* when he wrote, “transparency sheet to let light in.” Noelle’s justification for the transparency sheets was less obvious, since she wrote, “transparency sheets worked well on the sides because they are good at radiating heat.” She knew that radiation was part of the justification, but her wording does not make her scientific conception clear. Similar to Noelle, Marie attempted to justify the transparency sheets, but her statement that, “I chose the transparency sheet because it gets to the highest” is fairly vague. Marie, Noelle, and Sheldon agreed to use transparency sheets for the sides because the cooker container with transparency sheet sides had the highest temperature increase when tested during the first round, but their ability to relate this increase to conceptions about radiation was mixed.

Similarly, the team demonstrated a mix of conceptions about metals and conduction when discussing the bottom of the container. One of the first elements that the student team agreed on for the redesign was to put copper wire, along with aluminum foil, on the bottom of their second cooker container. All four team members spoke and/or wrote about the idea that *copper wire and aluminum foil are good conductors*, which is part of the scientific conception that *heat transfers more quickly through metal (conductors) than through plastic, paper, or wood (insulators)*. Even Dylan demonstrated this scientific conception, writing about another team’s design in Lesson 10, “The reason they had the largest temperature change is because they put copper on the bottom and metal is copper wire and metal heats up fast.”

What the team disagreed on was how to apply the idea that *metals are good conductors* to the second cooker container design. During Lesson 10, Marie proposed using copper wire on the bottom and the sides of their second prototype. Sheldon argued against putting the wire on the sides, asking, “Why would we put it up here when it’s not touching anything?” After some debate, Sheldon convinced Marie to leave the metals on the bottom only for the second cooker container. However, when the team discussed what they would do for a third design, Marie and Noelle both wanted to create an entire box – bottom, sides, and top – out of copper wire. Here, the team members were split. Sheldon and Dylan both continued to want to place copper wire on the bottom of the container only, recognizing that *conduction occurs at the bottom of the cooker container*, which is based on the larger scientific conception that *conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas*. On the other hand, Marie and Noelle both wanted to use copper wire everywhere because they had the alternative conception that copper wire transfers heat quickly regardless of context (i.e., no distinction between conduction and radiation).

One note worth mentioning about the idea of putting copper wire everywhere is that placing metals on the sides of the cooker container may not have necessarily been a poor design choice. If the students had proposed placing metals on the sides so that radiation/light energy would be reflected into the container, this idea would be based on scientific conceptions. However, that was not the idea that Marie or Noelle proposed. They stated that they wanted to put copper wire everywhere because it was a good conductor, which shows a lack of distinction between how the heat transfer processes of conduction and radiation affected the cooker container.

In summary, the process of learning from failure and redesigning generally helped the student team use more scientific conceptions and apply them to the engineering challenge more correctly. This led them to create a much better performing second cooker container prototype. They still demonstrated a couple of alternative conceptions about heat transfer during this process, but their use of scientific conceptions was more prevalent.

5.3.2 Connections to Other Literature about Redesign

Having the opportunity to learn from failure and redesign has been shown to be important for students' learning of science and performance in engineering design in several other studies about design-based activities. In this study, the student team learned from their own poor design choices with the first cooker container prototype, which has been seen elsewhere (Barnett, 2005; Sadler et al., 2000). This led them to create a more successful design solution during the second round of solution generation, which is similar to other studies that have shown that design performance tends to improve with iteration (Apedoe & Schunn, 2012; Schnittka, 2012). Other studies have shown that students who iterate more tend to learn more science content (Chao et al., 2017) and that students tend to use more relevant science ideas during the second or third iteration of design (Hmelo et al., 2000; Puntambekar & Kolodner, 2005). Similarly, the student team in this study used more scientific conceptions during the second round of solution generation than the first, and they applied those heat transfer conceptions more correctly to the design of the second prototype. The opportunity to learn from failure and redesign helped the student team use more scientific conceptions about heat transfer and improve the performance of their second design.

5.4 Develop Teamwork and Communication Skills: Summary of Results and Connection to Literature

This section focuses on answering part of the second research question, specifically how teamwork and communication influenced students' use of heat transfer conceptions as they participated in an engineering design-based STEM integration unit. During the *Ecuadorian Fishermen* unit, students frequently worked in their teams, or small groups. In addition to communicating within their team, they also used communication skills when they participated in whole class discussions and kept records of their science and engineering learning in their engineering notebooks. Both of these features of engineering, teamwork and communication, influenced their use of heat transfer conceptions.

Because students frequently worked in teams, they were able to learn various heat transfer conceptions from each other. However, that "learning" worked in both directions; sometimes they learned scientific conceptions from their peers, and other times they learned alternative conceptions from their peers. An example of learning scientific conceptions from their peers occurred when students considered the bottom of the cooker container prototypes. When they generated initial design ideas, Marie did not consider conduction at all, and it is unclear what Dylan was thinking about. However, Noelle and Sheldon both had put metals on the bottom for their ideas, and so the team's first prototype had an aluminum foil bottom. After the results of the first round of testing, all four team members solidified the conceptions that *metals are good conductors*, which is part of the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. (The team still disagreed about where conduction occurred in the cooker container, but they all agreed that metals conducted heat. See section 5.2.1.) In this example, they learned a scientific conception from their peers and from the results of prototype testing.

However, team members also "learned" alternative conceptions from each other. For example, during the first round of solution generation and continuing into the second round, the team had several alternative conceptions about the thermal properties of wood. At first, Noelle used the alternative conception that wood absorbs radiation/light energy. Later, Marie started to say the alternative conception that wood is a good conductor. Eventually, Sheldon also began to use the conception that wood is a good conductor. This alternative conception was never corrected because although the team ultimately decided against using wood in their second cooker container prototype, they did so for reasons unrelated to thermal properties. Another example occurred during Lesson 7 when students were answering questions about thermal properties of materials. The first question asked them to identify which materials would be good conductors. At first, Marie, Noelle, and Sheldon debated whether they should write “metals” or whether they should identify a specific metal object, such as a steel washer, to answer the prompt. However, when Marie noticed the radiation lab data table on the front board, in which the white felt had the highest temperature gain, she pointed this out to her teammates. For the remainder of the activity, the student team used the radiation lab data to answer questions about conduction and insulation, ultimately creating the alternative conceptions that white felt is a good conductor because it had the highest temperature increase (during the radiation lab) and aluminum foil is a good insulator because it had the lowest temperature increase (during the radiation lab). In these two examples, one member of the student team ultimately led to the whole team sharing similar alternative conceptions about heat transfer.

The examples given show that for the student team in this study, the pedagogy of collaborative learning (Johnson & Johnson, 1994; Johnson et al., 1981; Kagan, 1992) allowed students to learn both scientific and alternative conceptions from each other. Other studies have suggested that when students discuss their alternative conceptions with their peers, they are able to correct those conceptions and build scientific knowledge structures as a group (Mathis et al., 2018; Riskowski et al., 2009). This was true for the student team in some instances, for example, when Marie and Dylan learned from Sheldon and Noelle during the first round of solution generation that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. However, in other instances, sharing their alternative conceptions with their team members led the rest of the team to “learn” that alternative conception (such as, when they all began to agree that wood is a good conductor). For the student team in this study, working collaboratively did not always lead to science learning, but in some instances it did.

Another interesting note about teamwork is that in an effort to include everyone's ideas, the student team ultimately created a poorer first cooker container prototype. At the end of Lesson 8, Mr. Parker asked students which solution their team chose and why. Both Sheldon and Noelle described how the team "combined all of our solutions together," and Sheldon added, "because they all had good ideas." However, no one on the team yet realized that combining the ideas of having a black felt interior with a mostly white felt top ended up being a poor design choice. Each of these ideas on their own were justifiable in terms of scientific conceptions, but when they were combined did not allow for much radiation to reach the black felt so the black felt could absorb it. By trying to include at least one idea from each team member, the team's first cooker container prototype had a couple of design elements based on scientific conceptions that combined to create an unscientific whole. This result is similar to another study in which high school students who had completed several design-based activities were interviewed (Berland et al., 2013). When asked how they resolved disagreements in their teams, they said that although they sometimes used science and mathematics, they also relied on other factors such as social relationships. This result reflects what the student team experienced, which is that sometimes social norms, such as making sure that everyone is included, factor into design decisions, sometimes at the expense of correctly applying scientific conceptions.

Another way in which the student team learned from their peers was when the whole class evaluated the results of the first cooker container prototypes. All six teams in the class recorded a description of their prototypes, as well as the prototypes' costs and temperature increase results, on the front white board in the classroom. Additionally, Mr. Parker asked the team whose prototype had the largest temperature increase to explain and justify their design elements, and Mr. Parker also pointed out the similarities between the two prototypes with the largest temperature increases. From their subsequent written responses and discussions, it was clear that the student team learned from these more successful designs. In particular, this whole class discussion led the student team to use transparency sheet walls and copper wire on the bottom of their second cooker container prototype, and they even justified their choice of transparency sheet walls with the fact that the team whose prototype had the highest temperature increase used the same material. By seeing the results of other teams' prototypes, the student team was better able to apply scientific conceptions to their second cooker container prototype.

This phenomenon of learning from other teams in the class, including learning about which design elements were more successful, was also noted as an important student learning experience in other design-based activities (Hmelo et al., 2000). This phenomenon tends to be even more effective when these whole class discussions are guided by an instructor (Puntambekar & Kolodner, 2005), as Mr. Parker did in this implementation of the *Ecuadorian Fishermen* unit. Another study suggested that this kind of whole class discussion is especially effective for science learning and design performance when each student team is allowed to explain and justify their designs and also answer questions from their classmates (Puntambekar & Kolodner, 2005). However, the student team in this study did not have an opportunity to present their design to the class, so they were not able to experience science learning though explaining and justifying their design to their peers.

The student team also communicated by writing in their engineering notebooks. This written documentation contained a fairly accurate depiction of how their use of heat transfer conceptions changed throughout the *Ecuadorian Fishermen* unit. During the science-focused lessons of learn (about the problem), the students wrote statements that mostly reflected scientific conceptions. However, as they attempted to think about the multiple processes of heat transfer at once during Lessons 6 and 7, their notebook entries demonstrated their confusion. During these lessons, they recorded statements that were a mix of scientific conceptions and alternative conceptions, and they also left several prompts blank. These entries were indications that the student team was confused about the processes of heat transfer. Evidence of this confusion was also seen throughout much of the first round of solution generation, with some improvement during the second round of solution generation. Another important note about the notebook entries is that for many lessons, they were the only representation of Dylan's heat transfer conceptions. Dylan rarely participated meaningfully in the small group discussions, and she only participated in one whole class discussion, so her engineering notebook was essential in terms of interpreting her science conceptions. In this way, the engineering notebooks were a feature of engineering that helped reveal the students' heat transfer conceptions, both to the researcher and to the teacher.

However, in a few cases, the student team's written documentation overly simplified their heat transfer conceptions. The best example of this is to compare the design plan documents for the student team's first and second cooker container prototypes. In the first design plan, the team wrote the following statements: "The foil conducts the light," "The black and white felt absorb the light that the foil conducts," and "All the heat and light that is radiating to the foil and felt will absorb and conduct to the fish." Although these statements indicate several alternative conceptions, they did not indicate the use of any scientific conceptions nor did they indicate all of the alternative conceptions that the team used as they planned their first prototype, as evidenced by their conversations. In the second design plan, the team wrote: transparency sheet sides "because the team who got the highest temperature," copper wire and aluminum foil bottom "are very good conductors," and black felt top is "good at absorbing light." All three of these statements seem to be based on results from prototype testing or scientific conceptions about heat transfer. However, this document does not reveal that the student team had other scientific conceptions, nor that they still had a couple of alternative conceptions. These documents demonstrate a shift from students using only alternative conceptions to students using only scientific conceptions, both of which are oversimplifications of the range of heat transfer conceptions that the student team used.

Other research has shown that using engineering notebooks in design-based activities has generally positive effects. Similar to other studies (e.g., English et al., 2013; Gale et al., 2018), the student team in this study wrote about several science conceptions that were relevant to the engineering challenge in their engineering notebooks. In this study, the student team revealed many of their scientific and alternative conceptions about heat transfer in their notebooks. During the first and second rounds of solution generation, the student team tended to write about their heat transfer conceptions when they were responding to prompts asking them to explain and justify their design ideas, which is similar to results of other design-based activities (Mathis et al., 2018; Puntambekar & Kolodner, 2005). By writing about their heat transfer conceptions, they were able to demonstrate their science and engineering learning in a way that a pre-post assessment could not have done. Doppelt et al. (2008) stated that using a portfolio or notebook to evaluate students' science learning is especially important for certain groups of students, such as those who struggle with reading and writing. In this team, the engineering notebook was most important for Dylan to show her heat transfer conceptions because she rarely spoke about them in the small group or whole class. However, the notebook was important for all members of the student team, not only to demonstrate their heat transfer conceptions, but also as a tool to refer to when they could not remember an idea from a previous lesson.

Another engineering notebook feature that was interesting was the letter to the client activity at the end of the unit. These letters were meant to be an opportunity for the student team to demonstrate much of their knowledge about heat transfer as they explained and justified their recommended cooker container design. However, the student team members put varying amounts of effort into the letter, lessening its impact for two of the members of the student team. Sheldon and Noelle's letters were fairly complete, with both students attempting to justify their three main design elements: the copper wire/aluminum foil bottom, transparency sheet side, and black felt top. However, Dylan did not complete a description of the design, and she only justified why the team used black felt on the top. Similarly, Marie provided a more complete explanation of the design, but she did not justify any design elements and therefore did not use any heat transfer conceptions. The students' lack of enthusiasm and effort for end of the unit was likely related to the fact that they had completed most of the unit before winter break and only needed to finish up the end of Lesson 11 and then Lesson 12 after the break. By the time the class reached the letter to the client activity, they put noticeably less effort into the few remaining activities because they were ready to move on to another unit.

The heat transfer knowledge demonstrated by the students in the client letter varied. On the one hand, three of the four student team members wrote about at least one heat transfer conception in their letters to the client, and two members each justified three different design elements with heat transfer conceptions. This result is similar to another analysis of students' written recommendations to a client in a different design-based activity, in which 69% of the student referenced relevant science concepts related to their design (Gale et al., 2018). On the other hand, Marie's lack of science conceptions in her letter does not indicate her actual knowledge of science conceptions, since she wrote about heat transfer conceptions in other areas of the notebook. In this sense, Marie missed an opportunity to reflect on her design justifications, an activity that Wendell and Lee (2010) argue is critically important to science learning. Other authors have made a similar argument about final design presentations to the rest of the class, that explaining and justifying design solutions, as well as answering questions from peers, can be important for student learning (Hmelo et al., 2000; Puntambekar & Kolodner, 2005). Although Mr. Parker had the class write letters rather than give presentations, the idea that a final design communication can be an important learning activity for students is still true.

Finally, the vocabulary section of the engineering notebooks was meant to help students but ultimately hindered their use of heat transfer conceptions. Although it was not included in the *Ecuadorian Fishermen* curricular documents, Mr. Parker moved some of the key terms of the unit to a separate “Vocabulary” section in the back of the students’ engineering notebooks. This was meant to help the students because they had a similar section in their regular science notebooks. However, Mr. Parker only moved certain key terms (e.g., conduction, conductors, insulators) to this section, but not others (e.g., convection, radiation, absorb light, reflect light, transmit light). This was one factor that led to the student team’s confusion in Lesson 6 and 7. In order to compare the three methods of heat transfer, they turned to their Vocabulary sections in their notebooks, but then they became confused when some of the terms they needed were there and others were not. In this way, the separate Vocabulary section in the students’ engineering notebooks hindered their ability to think about the three processes of heat transfer.

5.5 Summary of Results: Conclusions

This section provides a brief summary of the results across all four components. In this concluding section, both research questions are answered broadly.

5.5.1 What Scientific and Alternative Conceptions about Heat Transfer Does a Team of Middle School Students Use?

The main result of the first research question is that the middle school student team used many scientific and alternative conceptions about heat transfer. (See Table 4.1 for a full list of conceptions used, as well as when the team used them.) For some heat transfer concepts, the student team used scientific language that implied scientific conceptions when other literature shows that middle school students typically use alternative conceptions. The students seemed to distinguish between “temperature” and “heat,” consistently using “temperature” as a property of an object. They also usually used the term “heat” in scientifically acceptable phrases based in kinetic molecular theory rather than caloric theory, such as “heat transfer” and “conduct heat.” Although they were introduced to the term “thermal energy,” they only used it twice and instead used “heat” in most cases where “thermal energy” would have been more appropriate (e.g., “heat transfer” instead of “thermal energy transfer”). However, because experts often use “heat” in this way, it likely did not represent an actual alternative conception but rather demonstrated that the students could communicate using language similar to experts.

The student team demonstrated other scientific conceptions when other students their age sometimes demonstrate alternative conceptions. For the most part, the student team talked and wrote about "hot air" or "hot water" rising, which represents the scientific conception that *hot fluids rise* rather than the common alternative conception that "heat rises." They consistently used the scientific conception that *the direction of heat transfer is from hotter objects (i.e., objects with higher temperature) to colder objects (i.e., objects with lower temperature)*, and they always used "cold" appropriately as an adjective; both of these conceptions contrast with a common alternative conception that cold is a substance, the opposite of heat, that moves. The most notable scientific conception was that the students not only learned the scientific conception that *materials at the same temperature can feel different because they transfer heat at different rates*, but they also turned this conception into a rough heuristic for identifying conductors by feeling objects at room temperature: *a material that feels colder will transfer heat faster (i.e., is a better conductor)*.

When it came to the heat transfer processes of conduction and radiation, the students used a greater mix of alternative conceptions. At first, the team used the scientific conception that *heat transfers more quickly through metals (conductors) than through plastic, paper, or wood (insulators)*. However, they then became confused when they used the radiation lab data to answer questions about conduction, creating the alternative conceptions that <u>white felt is a good conductor because it had the highest temperature increase (during the radiation lab)</u> and that <u>aluminum foil is a good insulator because it had the lowest temperature increase (during the radiation lab)</u>. By the end of the unit, though, they had returned to consistently using the scientific conception about metals as conductors. However, they also demonstrated two conceptions about what conduction fundamentally was. In some instances, they used the scientific conception that *conduction is the transfer of heat energy through a solid or from a solid to another solid, liquid, or gas* and thus conduction occurs where two objects touch. However, in other instances, they used the alternative conception that <u>copper wire transfers heat quickly regardless of context (i.e., no distinction between conduction and radiation)</u>. For radiation, the student team mostly used scientific conceptions, such as *dark colors absorb radiation/light energy better than light colors* and *metals reflect radiation/light energy*. However, they struggled to apply these radiation conceptions correctly to the design of a container.

Finally, the student team created several alternative conceptions that were not found in literature, all of which were related to conduction and/or radiation. Many of them occurred when the students confused conduction and radiation to create one set of rules about how well materials transfer heat; several of these alternative conceptions are listed in the previous paragraph.

Additionally, the team struggled to determine the thermal properties of wood, using the alternative conceptions that wood absorbs radiation/light energy and wood is a good conductor.

In sum, the student team used many scientific and alternative conceptions about heat transfer. For conceptions about heat and temperature, the team mostly used scientific conceptions and language. However, for the topics of conduction and radiation, the team used a mix of scientific and alternative conceptions, and many of these alternative conceptions stemmed from the team's confusion about conduction versus radiation.

5.5.2 How Do Engineering Design, Redesign, Teamwork, and Communication Influence Students' Use of These Heat Transfer Conceptions?

The results show that the key features of engineering (i.e., engineering design, redesign, teamwork, and communication) influenced students' use of heat transfer conceptions in different ways. During much of the problem scoping stage, which included the science lessons focused on heat transfer, students mostly used scientific conceptions about conduction, convection, and radiation when they learned about each of these processes of heat transfer separately. However, when they needed to think about those three processes of heat transfer together, as well as apply them to the context of the engineering design challenge, the students began to use a larger mix of scientific conceptions and alternative conceptions. Several alternative conceptions emerged when they combined ideas and vocabulary from conduction and radiation to create one set of rules about thermal properties of materials (i.e., did not distinguish between conduction and radiation). For example, when explaining their design plan, the team wrote the alternative conception, "The black and white felt absorb the light that the foil conducts." Even when they used scientific conceptions, the students sometimes applied the conceptions unscientifically when designing. For example, after Noelle chose to put aluminum foil on the exterior sides of their cooker container prototype, Marie explained this choice using the scientific conception that *metals reflect radiation/light energy*. However, no one on the team realized that because the metal was placed on the exterior of the container, the radiation would be reflected away from the container. This mix of alternative and scientific conceptions, the latter of which were sometimes applied correctly and sometimes incorrectly, led the team to create a prototype that performed poorly. In other words, during the process of engineering design, especially during the transition from the science-focused lessons of problem scoping to solution generation, the team began to use a greater mix of scientific and alternative conceptions about heat transfer.

The student team then learned from the failures of their first design, the successes of other teams' designs, and had the opportunity to redesign. During this second round of solution generation, they appropriately used many scientific conceptions. In particular, they were better able to distinguish between conduction and radiation and the thermal properties associated with each process of heat transfer. Ultimately, they created a second cooker container prototype that performed much better (i.e., achieved a higher temperature) during the solar oven test. In sum, the opportunity to learn from failure and redesign was critical to this team's use of scientific conceptions about heat transfer.

Teamwork and communication through engineering notebooks also influenced their use of heat transfer conceptions. The student team frequently worked as a small group, and as such, they demonstrated that they learned various heat transfer conceptions from each other. However, they "learned" both scientific and alternative conceptions from each other. Another factor about teamwork that negatively influenced the team was that they tried to include at least one design idea from each team member, but in doing so, they created a poorer prototype. They combined individually scientific conceptions about radiation but did not realize that the conceptions would not work well together. In contrast, the student team learned several scientific conceptions from their peers on other student teams, especially after the first set of prototypes had been tested. Because the student team had access to information about each team's prototype design and performance, they were able to reason through why some designs succeeded and other designs did not, which ultimately led them to use more scientific conceptions.

Engineering notebooks proved to be somewhat helpful for students, since they referred to them a few times when designing, but more importantly they were helpful in revealing students' conceptions, especially for Dylan because she rarely spoke. The students' engineering notebooks provided a fairly accurate depiction of their heat transfer conceptions, both scientific and alternative. Although the notebooks were generally positive in the sense that students could and did use them as a reference, there was at least one aspect of the notebooks that seemed to negatively influence their use of scientific conceptions. Mr. Parker chose to create a separate "Vocabulary" section but only moved some key terms to this section. When the student team needed to distinguish between convection, conduction, and radiation, they turned to this Vocabulary section but then became confused when it only contained information about conduction. One feature of the engineering notebooks, the final letter to the client, varied in terms of its influence on student science conception use. For Noelle and Sheldon, their recommendation of a design to the client allowed them to use three heat transfer conceptions, mostly scientific, to justify the team's design solution. Dylan used one scientific conception about heat transfer, which was a promising result, given that she often did not complete other notebook prompts. In contrast, Marie did not provide any heat transfer conceptions or justifications at all during the final letter to the client, so it was not as impactful for her. In sum, the engineering notebooks somewhat helped the students use heat transfer conceptions during the engineering design-based STEM integration unit, but they were especially important as a means for assessing their conceptions.

CHAPTER 6. IMPLICATIONS FOR RESEARCH AND PRACTICE

In this section, I describe implications for researchers and recommendations for future research. I then describe implications for practice, specifically for the *Ecuadorian Fishermen* curricular unit and also more generally for curriculum developers and teachers of engineering design-based STEM integration units as well as researchers in science and engineering education.

6.1 Recommendations for Future Research

By using an embedded case study research design, I was able to deeply explore how one student team used scientific and alternative conceptions about heat transfer throughout an engineering design-based STEM integration unit. Although I discovered important results about how certain features of engineering influenced the students' ability to use heat transfer conceptions, as well as results about what scientific and alternative conceptions they used, the study was limited in the sense that it was about one team of four students. Therefore, one recommendation for future research is to do similar analyses with other student teams participating in the *Ecuadorian Fishermen* curricular unit to explore what heat transfer conceptions they use, whether those conceptions are scientific or alternative, when they use the conceptions throughout an engineering design process, and how well they are able to apply those conceptions when designing an engineering solution. This research would be especially valuable if done with a variety of student teams, not only in terms of a greater diversity of demographics of students, but also including teams who applied science well and created high performing prototypes, as well as more typical teams who created average performing prototypes.

Another recommendation for future research comes out of the limitations of this study. This study occurred in a naturalistic setting, which meant that students' heat transfer conceptions were interpreted from their spoken and written communication during the unit. In order to more deeply probe students' conceptions, assessments and/or interviews that are designed to uncover students' conceptions could be implemented before and after, and also perhaps during, the unit about heat transfer. I acknowledge that giving students an assessment or interview before the unit may influence their participation and learning in the unit. In Lesson 1 of *Ecuadorian Fishermen*, students are meant to discover the idea that they will need to learn more about heat transfer in order to design a successful solution to the engineering problem. Therefore, asking them about their heat transfer conceptions before the unit may limit their discovery of this idea. However, this lessened discovery could be outweighed by the advantages of gaining a better understanding of students' preconceptions about heat transfer.

Additionally, future research could explore students' use of science conceptions during other engineering design-based STEM integration curricula, including curricula that have science foci in life science, earth science, and physical science topics other than heat transfer, and also curricula for different grade levels. These explorations could reveal whether certain features of engineering that influence students' use of science conceptions are specific to certain science topics or age groups, or whether they affect students' use of science conceptions more generally.

In particular, engineering notebooks could be further explored with more diverse populations. During this study, notebooks were a consistently valuable tool to discover students' conceptions about heat transfer, especially for the student who rarely spoke in small group and whole class activities. Therefore, implementing notebooks could provide an opportunity for researchers to explore conceptions within a diverse population, including students who do not typically reveal their conceptions through spoken language.

Other possibilities for future research are to continue adding to the research literature about heat transfer in education settings. This study adds to the literature that the language of heat transfer is problematic and makes heat transfer concepts especially difficult to learn. Therefore, research continues to be needed about how to best introduce students to the scientific language of heat transfer and help them differentiate between scientific language and everyday language. This type of research could also be combined with intervention studies about using notebooks for the purposes of learning heat transfer conceptions. An additional area of needed research is students' conceptions about thermal radiation, as well as their conceptions when they are learning about multiple processes of heat transfer in the same curriculum. There is little literature about conceptions of thermal radiation. Furthermore, the students in this study demonstrated numerous alternative conceptions that stemmed from their confusion about the heat transfer processes of conduction and radiation. Thus, it is important to explore these conceptions and also how various interventions can be used to help students gain scientific conceptions about the three processes of heat transfer.

6.2 Implications for Practice

6.2.1 Implications for the *Ecuadorian Fishermen* Curricular Unit

By studying an in-depth case of a student team as they participated in the *Ecuadorian Fishermen* curricular unit, I have a few recommendations for changes to the curricular unit itself. All of the changes are meant to help students to more easily learn and use scientific conceptions about heat transfer.

First, I recommend introducing the key terms "conduction," "conductor," and "insulator" earlier in Lesson 3. In the existing curricular documents, the terms and their definitions were introduced at the end of Lesson 3 so that students could learn about the concepts themselves before being introduced to the specific terminology. Although that worked during the lesson, the student team generally struggled to use these terms appropriately later in the unit, in part because they had not practiced them during Lesson 3. Second, the radiation lab in Lesson 4 needs to be overhauled so that it does not result in conflict. For the most part, the student team had the scientific conception that *dark colors absorb radiation/light energy better than light colors* before the radiation lab. However, when the white felt reached a higher temperature than the black felt, this caused confusion in the sense that their scientific conception did not align with the experimental results. This confusion carried over into the first round of solution generation, with the student team using both white felt and black felt in their design with "appropriate" justifications for both.

Third and most important, the lessons that were designed to help the students transition from learning (about the problem) to planning (a solution), i.e., Lessons 6 and the first part of 7, need to have better scaffolding to help students think about the three processes of heat transfer at once. These lessons were critical for the student team, and it was during these lessons that they first began to confuse ideas and vocabulary from conduction and radiation.

One step that could be taken during Lesson 2-5 that may help students during Lessons 6-7 is to use easily accessible visuals that summarize the three processes of heat transfer – conduction, convection, and radiation – as well as the thermal properties of materials in conduction and radiation. For example, a teacher could create anchor charts, one for each process of heat transfer. The conduction anchor chart could include information about not only the process of conduction, but also which materials are typically conductors or insulators. A similar anchor chart about radiation could include information about which materials absorb, reflect, or transmit light. Instead of relying on students to look at information in their notebooks, the main points about heat transfer processes and thermal properties would be summarized and easily visible so that students could use the anchor charts as a reference.

In Lesson 6, I recommend reversing the order of the activities so that students first review the three processes of transfer, including the compare and contrast prompt as well as the review activity that Mr. Parker chose to implement as a Quizizz game, and then apply those concepts to the context of the solar oven by determining how each process occurs within the solar oven. It may also help to reverse the order in which students think about each heat transfer process, starting with the most recent (i.e., radiation) and ending with the one first introduced in the unit (i.e., convection). For the student team, because they wasted so much time trying to remember what convection meant, they were not able to discuss conduction or radiation. Reversing the order of the terms during the review activity may have helped them, since they would have started with the process they had most recently covered and worked backwards.

I also recommend changing the Lesson 7 activity in which students determined the thermal properties of the available design materials. In the existing curricular unit, the activity is given to the students as a set of five prompts, with the first two questions about thermal properties in conduction and the last three questions about thermal properties in radiation. However, because it was presented to the students as simply a list of five questions, the student team did not make a distinction between the two sets of questions and therefore did not distinguish between conduction and radiation. (It did not help that Mr. Parker left the radiation lab data on the front white board which the student team then used to determine properties about conduction, but that was a choice in implementation, not the unit itself.) Therefore, I recommend reorganizing the prompts in such a way as to make the distinction between conduction thermal properties and radiation thermal properties more evident, as well as clarifying to students that the design materials should be used in both sets of thermal properties. (For example, aluminum foil can be a conductor in conduction but also can reflect light energy in radiation.) This reorganization could be done visually by creating a better graphic organizer, or perhaps the activity could be divided into two sequential smaller activities, with students first focusing only on conduction and then only on radiation. Either of these methods, or perhaps a different one, should be used to help clarify the activity to students, since as it is written, the student team became very confused while doing the activity.

For the rest of the *Ecuadorian Fishermen* curricular unit, I do not recommend making any major changes. Although the student team used several alternative conceptions during the first round of solution generation, many of these conceptions stemmed from their confusion in Lessons 6 and 7. Also, I do not recommend changing the final lesson, Lesson 12: Communicating with the Client. The communication to the client activity was meant to serve as way for students to demonstrate their heat transfer conceptions as they explained and justified their recommended design solution. In this study, though, not all of the student team members demonstrated their science learning during this activity. However, I do not think this reflected the activity itself but rather the poor timing of the activity. Therefore, I do not recommend changing this lesson, nor any of the other activities in Lesson 8-12.

6.2.2 Implications for Curriculum Developers and Teachers

For this student team, there were a couple of critical lessons within an engineering design process, during which the student team began to use more alternative conceptions. Although members of the student team had demonstrated mostly scientific conceptions about heat transfer during the learn (about the problem) lessons in which each process of heat transfer was considered on its own, they became confused in Lessons 6 and 7 when they were required to not only think about the three heat transfer processes simultaneously but also apply them to the context of the engineering challenge. During these lessons transitioning the students from learn (about the problem) to plan (a solution), they created several alternative conceptions in which they combined ideas and vocabulary from conduction and radiation to form one set of thermal properties (i.e. did not distinguish between conduction and radiation), and they continued to use alternative conceptions of this type as they attempted to design an initial solution to the engineering problem.

For curriculum developers and for teachers, this result implies that careful attention needs to paid to this transition between problem scoping and solution generation when designing and implementing engineering design-based STEM integration curricula. These curricula need to provide scaffolds for students to combine the various science conceptions they have learned thus far in the unit and also to use these conceptions together to understand the context of the engineering challenge. If students start the solution generation phase with lower level but still scientific conceptions, then they will likely be better able to use higher level thinking skills to apply these scientific conceptions when designing engineering solutions. Teachers also need to be wary of this transition period, being careful to notice if students become confused and begin to generate alternative conceptions. If alternative conceptions are noticed quickly, teachers can review science concepts to address them before students start applying them to their designs. In these ways, curriculum developers and teachers can lessen the increased use of alternative conceptions that can occur during the transition from problem scoping to solution generation.

In contrast, there was one main feature of engineering that helped the student team improve their use scientific conceptions about heat transfer during engineering design: the process of learning from failure and redesign. After the student team observed other teams' prototypes and their results during testing, they were able to learn from the failures of their first design and also from the successes of other student teams. Then during the second round of solution generation, in other words during redesign, they were able to use more scientific conceptions and fewer alternative conceptions, resulting in a better performing and more scientifically sound prototype.

For curriculum developers and teachers, this result implies that the process of learning from failure and redesign can be critically important to students' science learning, especially for teams who struggled to use scientific conceptions and thus created poor designs initially. When engineering design-based STEM integration curricula are developed, they should therefore include at least one opportunity for students to redesign. For teachers, it is important implement redesign activities. Because redesign tends to occur near the end of design-based curricula, it can be tempting for teachers to not implement redesign in order to save time. However, the results of this study imply that redesign needs to be included in design-based curricula, since it can be critical to some students' learning of scientific conceptions.

Another feature of engineering that was helpful was the use of engineering notebooks. For the student team, their notebooks provided them with a place to record heat transfer conceptions so that they could refer to them later in an engineering design process. These notebooks could also be useful for teachers, since they can show which scientific or alternative conceptions students have and how well they are able to apply those conceptions when solving an engineering challenge. Notebooks can be especially helpful for quieter students, since it provides them an opportunity to express their conceptions and ideas in writing, even if they are unable or choose not to express their conceptions during team or whole class discussions.

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