ABSTRACT

Title of Dissertation: “HOW DO WE MAKE THIS HAPPEN?” TEACHER CHALLENGES AND PRODUCTIVE RESOURCES FOR INTEGRATING ENGINEERING DESIGN INTO HIGH-SCHOOL PHYSICS

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Recent attention on social, civil, and environmental problems has caused policy-makers and advisors to advocate for more integrated science, technology, engineering and mathematics (STEM) instruction. Although integrated STEM education promises to prepare U.S. students to tackle the crises of our times and the future (Lander & Gates, 2010), the integration of engineering design into high-school physics may prove difficult for teachers whether or not they’ve been previously trained in engineering design. This dissertation addresses a gap in classroom

observation-based research on engineering integration in physics (Dare, Ellis, & Roehrig, 2014) by drawing on rich, qualitative, participant-observation data to investigate engineering-design instruction in high-school physics.

The first study explores tensions that three high-school physics teachers encountered as they planned and executed a terminal velocity engineering design challenge. Separating out physics content came into tension with truly integrated engineering-design instruction as envisioned in the Next Generation Science Standards (NGSS Lead States, 2013d), time and technical constraints came into tension with adequate data collection for making design decisions, and teachers' supportive classroom routines came into tension with students' divergent design thinking and agency. The first study concludes that even highly motivated and supported teachers may experience tensions between their regularly productive instructional practices and engineering design that could threaten the authenticity of the engineering design in which students engage.

The second study identifies some of teacher "Leslie's" productive resources (locally coherent patterns of thoughts and actions) activated as she implemented her first engineering design challenge in physics. Leslie called up some of the same resources when she taught engineering design as when she facilitated open, guided, and structured-inquiry investigations. This study suggests that finding and calling upon resources that are assistive in other instruction, such as inquiry instruction, might be useful for science teachers attempting engineering-design integration.

Science education reform implementation researchers, teacher educators, and professional development providers need to acknowledge tensions that teachers may face with engineering-design integration, and the role that teachers' existing resources can play in supporting reform adoption. Finally, this study agrees with other work (Katehi, Perason, Feder, & Committee on K-12 Engineering Education, 2009) emphasizing the need for more research on engineering-design integration in high-school physics.

“HOW DO WE MAKE THIS HAPPEN?” TEACHER CHALLENGES AND PRODUCTIVE RESOURCES FOR INTEGRATING ENGINEERING DESIGN INTO HIGH-SCHOOL PHYSICS

by

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Dissertation submitted to the Faculty of the Graduate School of the
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Dedication

For my mother.

Near the end of my mother's life, I applied to be an astronaut. Joking through her pain and fear, she said, "Katey won't be satisfied until she's back in Antarctica or in outer space." Pretty soon after that, she was gone. She didn't live to see me go back to Antarctica with my husband, climb on never-climbed ice slots, and learn about the simple currency of love, pebbles. She also didn't make it to see me go to Houston, twice, as I came the closest to becoming an astronaut as possible without making it.

If my mom had lived to when I was applying for grad school, she would have understood how it was closer to my heart than astronauts and Antarctica. Mom knew I was going to be a teacher before I could read. I played school on the porch while my sisters were at real school, but I was the teacher, and the dolls my pupils. (What does it say about how deeply ingrained direct instruction is in our culture, that a girl who'd never been to anything but Montessori preschool somehow knew that "school" would involve sitting still and listening, eyes front?)

Mom would have appreciated my incredible joy while spending a year at Merlin High School, and would have understood why I'm eager to get into the world to support teachers trying engineering integration. Engineering presents opportunities for boundless and useful creativity of teachers and students, and nothing makes my heart sing like creativity, except creativity and physics together.

I hope this dissertation contributes to providing students and teachers inroads to doing creative thinking in their high-school physics classes, and to inspiring future explorers of Earth and space for the rest of my life. Thank you, Mom, for remembering how big dreams matter and for making sure I kept them in front of me.

Acknowledgements

I owe my gratitude to my family, friends, colleagues and students for helping me and pushing me to finish this dissertation.

To my dad, thank you for never wavering in your steadfast support and reasoned guidance. You asked me on a spring day many years ago, Since you're in Charlottesville anyway, and teaching anyway, why don't you take some education classes? For that wise suggestion and all the thousands of others you've shared with me, thank you, Dad.

To my Ross and my Molly, you have provided me patient space, helpful support and a reason to finish. Let us rejoice and exchange pebbles!

To my family, thank you for asking, listening, and encouraging. Thank you Margaret and Rob, Liz and Frankie, Amy and Chris, Chris and Christine, John and Celeste, Dana, Isabel and Mike, and Zach.

To my real family, you know who you are. Thank you, Gina, for publishing first so I knew it was safe. Thank you Katie, Alison, Sarah, and Kate for keeping me around. And just thank you to all of you fabulous friends, Ellie, Rosie and Wes, Al and Irene, Joel and Erin, Jess and Patrick, Kate and Micah, Abbe and Tony, Will and Andrea, Jazmine, Dan and Ori, Warren, Leslie, Shal, Maggie, and Sonnie.

To my University of Maryland family, thank you for helping me turn a more skilled inquisitive eye on the world of teaching. Thank you to my committee, to

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To my Knowles Science Teaching Fellowship family, thank you for setting the bar high and welcoming me to reach it. Thank you Harry, Janet, Nicole, Dina, Roseanne, Liz, Lindsay, Anne, Jordan and Aaron, Jason, Kristen, Christy, Andrew, Matt, and Cathy. What am I without you?

To my IceCube family, thank you for teaching me the narrative arc and what it means to be responsive. Thank you Jim, Linda, Megan, Steve, Nancy, and Eric.

To my inspirations, the students I have taught, coached and learned from over the years. From two-year-olds to grown adults, so many of you are etched forever in my memory. You are here even now, my co-authors, my motivations, my hope, and my spirit.

To my teachers, all of my teachers, thank you for every late night, derogatory message, and poor paycheck you have endured. Your talent inspired me to try and to seek knowledge. Thank you to my participating teachers Katniss, Anna and Leslie, and to my mentor teachers: Tony, Ron, Bill C., Jen, Christy, Mary and Kate. Thank you for all of your advice, noticings, and wonderings. I’ve learned so much about teaching with you as my guides. And thank you to my foundational teachers: Mike F., Bill B., Randy, Deborah, Dan, Dave, Kip, and lastly Mike Z., who told me teaching is the noblest profession. He wasn’t wrong.

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ABET	Accreditation Board for Engineering and Technology
CER	claim, evidence, reasoning
CLT	cognitive load theory
CRP	culturally relevant pedagogy
CRT	culturally relevant teaching
DV	dependent variable
ETF	Engineering Task Force (former name of the KSTF Lever Engineering Group)
IB	International Baccalaureate
IV	independent variable
K-12	kindergarten to twelfth grade
KSTF	Knowles Science Teaching Foundation
m/s	meters per second
MBA	Master of Business Administration
NAE	National Academy of Engineering
NCLB	No Child Left Behind Act of 2001
NGSS	Next Generation Science Standards (NGSS Lead States, 2013)
NOE	Nature of Engineering
NOS	Nature of Science
NRC	National Research Council
NSES	National Science Education Standards (NRC, 1996)
NSTA	National Science Teachers Association
PBL	problem (or project)-based learning
PCAST	President's Council of Advisors on Science and Technology
PD	professional development
PhD	Doctor of Philosophy
PI	principal investigator
PLTW	Project Lead the Way®
PO	participant observation
STEM	science, technology, engineering, and mathematics
v-t graph	velocity versus time graph
v_t	terminal velocity
x-t graph	position versus time graph

Chapter 1: Introduction and Structure of the Dissertation

Physics teacher Leslie Knope (pseudonyms are used throughout) and her colleagues at Merlin High School, Anna and Katniss, were giggling and goofing around as they considered their first engineering design challenge. They had been asked to help a garden gnome, TV's David el Gnomo, get out of a post hole that he was stuck in. The teachers tittered as they scoped the problem. David, they estimated, was about the size of a bobble head; he could only reach as far as the length of his arms and could only jump a fraction of his height. They stood, jumped, reached, and measured, engaging immediately in the problem and deciding together what they needed to know about the limits of the challenge. (Just what is a tower? Could it be a ladder instead?) The teachers were learning an engineering design process as they went. Soon they would articulate it and compare it to a process recommended by national reform efforts for engineering-design integration. They were in the room to improve their engineering-design facilitation, but in the moment they were motivated to help David.

They were there working on a solution for David because of pressure to integrate the E into "STEM" in high-school physics. The STEM movement has taken center stage in United States education discourse due to below-international-average secondary-student performance in science and mathematics (Charles & Shane, 2006), and also due to international competition and industry demand for STEM graduates (Lander & Gates, 2010). The current national science education reform effort, the

Next Generation Science Standards (NGSS), mandates inclusion of engineering design in mainstream science courses like physics. The NGSS specifies that engineering design should be incorporated into existing science classes instead of creating new engineering class sections (National Research Council (U.S.), 2012). So current science teachers from kindergarten to high school are now tasked with including engineering in their curricula to meet these standards.

There has been plenty of research on why that is a good idea: engineering-design instruction helps widen students' problem-solving skill sets while providing authentic, i.e., real-world, contexts for learning science content (Apedoe, Reynolds, Ellefson, & Schunn, 2008; Bybee, 2006; Lander & Gates, 2010; Spillane & Thompson, 1997). Authentic contexts can help all learners but are especially beneficial for groups that are underrepresented in STEM, such as women and minoritized populations (Committee on a Conceptual Framework for New K-12 Science Education Standards, 2012; Delpit, 2012).

Unfortunately, there has been less research on how engineering integration happens in K-12 science classrooms. If engineering design is going to become a normal part of science instruction, then we must investigate the decisions and motivations of teachers as they conceptualize engineering design, plan engineering-design instruction, and teach engineering design alongside their still mandatory content curriculum. Research studies, such as this one, that investigate the challenges teachers experience during integration may be useful in designing aligned supports to meet teachers where they are for more successful implementation (Desimone, Porter, Garet, Yoon, & Birman, 2002).

In the 2015-2016 school year, I worked closely with Anna, Katniss, and Leslie to introduce the basics of engineering design to them and to co-plan, support, mentor, and aid in their reflection as they planned and taught engineering design challenges to their eight sections of 11th- and 12th-grade physics (about 200 students total) at Merlin. I collected qualitative observation and interview data (audio, video, and field notes) and met with the teachers frequently for scheduled planning sessions and informal discussions at lunch, after school, or just in the hallways.

This dissertation uses two studies to investigate how the three teachers took up and integrated engineering design into their practices. Specifically, I was interested in (1) what tensions exist in integrating engineering-design instruction reform in high-school physics, and (2) what resources (bits of reasoning expressed in locally coherent patterns of thoughts and actions), if any, assist a physics teacher in adopting engineering-design integration reform.

Each teacher was looking for slightly different experiences for their students and themselves, and at first it was hard to parse those out. But through careful observation, collegial planning, and interviewing, I came to understand more about what contributed to their decisions regarding physics and engineering teaching and learning. What I learned about the challenges and opportunities of bringing engineering-design instruction into content physics classes could be useful to any science teacher, science teacher educator, curriculum writer, or reform implementation researcher interested in integrating engineering design in K-12 science.

Structure of the Dissertation

This study was conducted to understand the difficulties associated with trying engineering-design reform in high-school physics. NGSS reform is a timely issue, and I am eager to share my observations and analyses with a wider set of teachers and reform advocates. Thus, my results are reported as "self-contained papers" to try to expedite the potential distribution of my findings.

The first part of the dissertation is in a familiar format: Chapter 2 is a literature review on engineering design, engineering design as envisioned for instruction in high-school science, issues of K-12 science teaching reform implementation, and the theoretical framework employed throughout the dissertation. Chapter 3 describes my study methods and provides a reference timeline that chronicles the study.

The second part of the dissertation has two chapters that are more intended to stand alone as journal submissions than dissertation chapters. Each chapter has its own literature review section and methods section tailored to the research question asked in that paper. Chapter 4 looks at all three teachers planning and teaching their Parachute Challenge to examine tensions that arose and how these three teachers negotiated them. Chapter 5 investigates teacher Leslie Knope's productive resources, i.e., bits of reasoning appearing in locally coherent patterns of thought and action, that were present in her physics instruction, and describes how they were called up, if at all, during engineering-design instruction.

Chapter 6 concludes my dissertation with a summary, and discusses implications and future directions of my research.

Chapter 2: Literature Review and Theoretical Framework

My dissertation seeks to understand the tensions that three high-school physics teachers experience, and the productive resources they draw upon, when they try to integrate engineering design into their classes as suggested by the newest national science teaching reform movement. This literature review explores that reform movement and addresses the following questions: How is engineering design envisioned in the goals and recommendations of the NGSS reform? What potential difficulties might we expect based on previous science teaching reform implementation? What challenges have emerged so far in the research on engineering-design integration in K-12 settings including physics? Also, what gaps exist in the research that has been done so far? Following the review, I explain my conceptual framework for teacher decision-making. This framework underpins my research questions and data analysis.

2.1 What is Engineering Design?

Engineering design is understood to be crucial to a vibrant technological society, but there is little consensus around what exactly engineering design looks like or how to teach the engineering design process. "Even 'design' faculty—those often segregated from 'analysis' faculty by the courses they teach—have trouble articulating this elusive creature called design" (Dym, Agogino, Eris, Frey, & Leifer, 2005, p. 103). Although drafting an exact definition of design may be difficult, engineers and engineering educators seem to agree that engineering design is complicated, creative, natural, and valuable.

The act of designing may be seen as “making something that has not existed before” (Petroski, 1992, p.vii) to satisfy a particular need in a particular moment in time, but it’s not that simple. Such overgeneralizations contribute to a “widespread feeling that the intellectual content of design is consistently underestimated” (Dym et al., 2005, p.104). Engineering design involves many actions to make something new or improved and requires complex cognitive processes. Dym et al. (2005) defined engineering design as “a systematic, intelligent process in which designers generate, evaluate and specify concepts for devices, systems, or processes whose form and function achieve clients’ objectives or users’ needs while satisfying a specified set of constraints” (p. 104). The designer makes hypotheses of structures (Petroski, 1992), predicting that the design will meet a need without fail for some duration. Failure and revision are natural in engineering design and design history and contribute to the underlying creative threads of the engineering profession.

Designers do *design thinking* as they “scope, generate, evaluate, and realize ideas” (Sheppard, 2003), and that too is seemingly hard to pin down. Some habits of mind or thinking skills that have been identified as part of the design process include tolerating ambiguity, keeping larger and smaller systems in mind, handling uncertainty, making decisions, thinking as part of a team, and communicating in several languages of design, including oral, written, and drawn languages (Dym et al., 2005).

Engineers investigate a problem based on client criteria and constraints, and they brainstorm multiple possible solutions and pick a solution based on relative merits and trade-offs (Katehi et al., 2009). Then they improve the solution through testing and optimization, and likely communicate the solution to the client. This series of steps is repeated cyclically as a whole, and pieces of it are repeated cyclically within the process.

These actions represent a holistic simplification from start to finish of the sophisticated and complex process that career engineers employ in parts, as defined by their career focus. It would be rare for an engineer at NASA to work on all parts of a Mars rover, say, from the beginning of problem definition all the way to the design of the form, the electronics, the sensors, the deployment, and the communication systems. The knowledge that informs decisions in these highly specialized areas can come from experimentation but is also situated in a wealth of content science background (physics, chemistry, calculus) learned in engineering schools.

2.1.1 College Engineering Instruction Separates Sciences from Design

If engineering design is so complex, subtle, nuanced, and mysterious, how can we teach it to others? Higher-education students practice engineering design as a start-to-finish learning experience in “case method” design and analysis courses (Grinter, 1955; Hoffman, 2014). But those courses can only “simulate as close as academically possible the activities in which engineers are involved” (Hoffman, 2014, p. 2) to give new engineering students “some flavor of what engineers actually do while enjoying an experience where they could learn the basic elements of the design process by doing real design projects" (Dym et al., 2005, p.103). Thus, it seems that even engineering education has to make generalizations of the design process to grant entrance to practicing it.

In college, the opportunities for design are few. Usually, students must complete several years of instruction on the "basic scientific principles as related to, and as related through, engineering problems and situations," (Grinter, 1955, p. 81) (like mechanics and fluid dynamics) before taking one to two "capstone" engineering design courses (Radaideh, Khalaf, Balawi, & Hitt, 2013) "directed toward the creative and practical phases of economic design, involving analysis, synthesis, development, and engineering research" (Grinter, 1955, p. 81). Documented disadvantages of this curriculum structure include low retention and lack of connection between content mathematics and science courses and engineering practice and careers. A combination of desires for increasing retention, developing problem-solving skills in context, and improving diversity and inclusion, and research on cognition (such as functional MRI imaging), has inspired the introduction of design courses earlier in the engineering education sequence and emphasis on integrated learning (Froyd & Ohland, 2005).

Recommendations for engineering design curriculum include the need for a contextual problem offering opportunity for multiple design outcomes, encouraging all of the requirements of engineering design, such as iteratively scoping and defining a problem, generating multiple ideas prior to idea selection, making decisions based on multiple forms of gathered information, and using failure productively, etc. Recommendations for course management include forming three- or four-student teams; utilizing student choice with instructor oversight and feedback ("students are required to get approval of the instructor to ensure that they have systematically undergone the necessary design iterations prior to prototyping" (Radaideh et al., 2013, p. 17)); instructor, peer, and self assessment; weighting later projects more than initial projects; and providing flexible technical lab and equipment support availability (ABET, 2013; Dym et al., 2005; Radaideh et al., 2013).

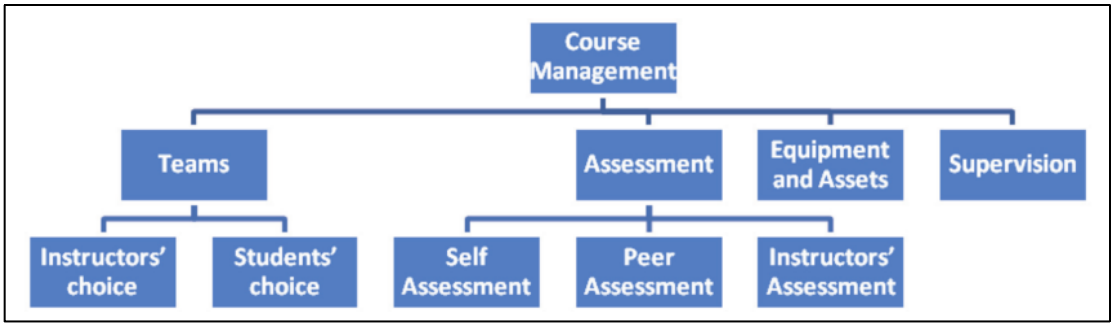

Figure 2.1 Course Management Diagram (Radaideh et al., 2013, p. 16)

Figure 2.1 Shows a course management diagram from Radaideh et al. (2013) that highlights several course factors echoed in the recommendations mentioned above..

Current recommendations for cornerstone engineering design at the university level (ABET, 2013; Christ, 2010; Radaideh et al., 2013) and recommendations for engineering-design integration in K-12 science (Katehi et al., 2009; National Research Council (U.S.), 2012; NGSS Lead States, 2013d; Truesdell, 2014) share many similar elements of technical and social imperative.

2.2 Engineering Design is Integrated into High-School Science

The newest era of science education recommendations, the NGSS (NGSS Lead States, 2013d), recommends integrating engineering into science content classes from Kindergarten through 12th grade. The NGSS includes engineering practices and engineering, technology, and applications of science content standards alongside the traditional science disciplines (life science, physical science, and earth and space sciences) as part of the "knowledge and skills that all students need in order to engage fully as workers, consumers, and citizens in the 21st Century" (NGSS Lead States, 2013a, p.107).

The NGSS (NGSS Lead States, 2013d) and its precursor, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (National Research Council (U.S.), 2012), included a novel push for engineering education embedded in science instruction at all grade levels, reflecting a national trend towards STEM integration, i.e., the need for combined instruction on science, technology, engineering, and math. The STEM trend in science reform was supported by economic competition with other developed nations, by recognition of STEM needs in environmental and climate solutions, by high-paying STEM careers, and by a desire for equitable learning and earning opportunities for traditionally marginalized groups of the population (Lander & Gates, 2010; President's Council of Advisors on Science and Technology, 2010).

Briefly, the recommendations suggest students will learn through doing engineering design, confronting context-rich, real-life design challenges that have social and global significance. More general and specific recommendations for instruction are discussed below in section 2.5.

Grinter (1955) called engineering analysis and design the most distinctive features of engineering curricula, and the NGSS agreed explicitly. Simplifying “engineering analysis and design” to “engineering design,” the NGSS and the *Framework* stated that engineering design is the hallmark of engineering. The NGSS stated that engineering design deserved explicit instructional attention unto itself as a problem-solving process as well as in the service of teaching new science content, supporting the practical application of science content, and providing motivational contexts for learning science (NGSS Lead States, 2013c).

2.2.1 Engineering Design to Teach Content Physics in Context

Engineering design problems provide a context for the application of physics content (Apedoe et al., 2008; Bybee, 2006; Lander & Gates, 2010) but also provide a space for learning how to solve problems and, in doing so, to learn new content, too. Learning to design is not just learning technical competence but also developing “a willingness to attack a situation never seen or studied before, for which data are often incomplete” (Grinter, 1955, p.81).

This statement has two implications for engineering in K-12. First, students may accumulate the data they need to solve a problem that they have not seen before but that the teacher or an expert has seen, and that can mean learning new content as an individual learner. Secondly, Grinter is referring also to solving problems never before seen in the world. He goes on, “It also includes an acceptance of full responsibility for solving the problem on a professional basis” (Grinter, 1955, p.81). The NGSS, the *Framework*, and the *President’s Council of Advisors on Science and Technology* (2010) all expect that the students of today will solve the biggest problems in the world tomorrow, and projects such as the Millennium Project from the University of Michigan and the National Academy of Engineering 2020 Project advocate for K-12 teachers to use global engineering challenges as instructional opportunities in their classrooms. It is widely believed that giant, unsolved, real-world problems are engaging and that engagement with these problems could lead to students accepting responsibility for them (Dym et al., 2005).

Locally and personally relevant contexts have been shown to improve student engagement and outcomes for girls and minorities (Delpit, 2012). Learning engineering design promises to increase student motivation, interest, and achievement by providing real-world contexts for learning and by widening students’ problem-solving skill set (Apedoe et al., 2008), especially for minoritized student groups who find contextual learning to be especially beneficial (Delpit, 2012; Lander & Gates, 2010). Learning about and through engineering design may help minoritized students in particular to attain better college readiness; improve interest, enrollment and retention for girls and minorities in STEM (President’s Council of Advisors on Science and Technology, 2010); and eventually contribute more equally to the technology and engineering labor force as “careers in science and technology require knowledge of mathematics, science, and engineering as well as skills in observing, describing, conjecturing, testing, designing and explaining" (Loucks-Horsley, 2003, p. 66).

The widespread underrepresentation of women and minorities in STEM fields underscores the need to improve the science and mathematics participation and achievement of these groups (Committee on Underrepresented Groups and the Expansion of the Science, Committee on Science, Engineering, National Academy of Sciences, National Academy of Engineering, & National Academy of Medicine, 2011; Lander & Gates, 2010; President's Council of Advisors on Science and Technology, 2010). Not only is the world missing out on the individual and collective skills, reasoning, and ingenuity of these groups when they are not in engineering, but these populations are missing out on the high-paying, career-sustaining jobs of engineering, technology, mathematics, and science.

Engineering design utilizes mathematics and scientific material, but also requires strong language and communication skills and teamwork skills. These and other so-called 21st-Century skills are necessary to prepare responsible, able citizens to work up to their full potential and to solve the problems that our society faces (Brophy, Klein, Portsmore, & Rogers, 2008; Committee on Underrepresented Groups and the Expansion of the Science et al., 2011; Radaideh et al., 2013). Engineering-design instruction may improve 21st-Century skills by teaching problem solving methods, divergent thinking, rational decision-making, empathy, ethical consequences of technological decisions, teamwork, and communication (Katehi et al., 2009). Understanding how physics teachers include engineering design in their instruction may support the development of future science students' 21^{st}-Century skills.

2.2.2 A Four-Phase Model for Engineering-Design Instruction

Defining engineering design is hard; therefore, models are suggested that guide practice. There are many such models in literature and instructional materials, probably because it's so hard to define. Though they may look qualitatively different, they share some features, and most try to represent engineering design as a cyclical or iterative process (usually with circles and two-headed arrows). Also, although the shape and form of an engineering design model may change, the essential steps of engineering design remain the same (Brophy et al., 2008; Truesdell, 2014), and many models reflect these as phases such as specifying, researching, making, testing, refining and evaluating (Dillon & Howe, 2007), or as define problem, develop solutions, and optimize solutions (NGSS Lead States, 2013d). Because some engineering design processes are repeated as necessary, and some parts may be broken down into smaller cycles, representations of any engineering design process can vary tremendously in complexity.

Radaideh, Khalaf, Balawi, and Hitt (2013) describe a four-stage model for higher education, which includes problem definition or framing, conceptual design, preliminary and detailed design and build, and design communication. This model is derived from Dym et al.'s (2005) "five-stage prescriptive model of the design process" with the 3rd and 4th stages (preliminary and detailed design stages) merged.

This model is relatively easy for me to understand, but clearly this and all other models are limited because they necessarily simplify the complexity and intricacy of engineering design to more usable, but less nuanced, representations (Dillon & Howe, 2007).

The NGSS (NGSS Lead States, 2013d) models engineering design for K-12 instruction in two ways. First, it lists eight practices of science and engineering (Figure 2.2); Second, it describes an interactive relationship between defining problems, developing solutions, and optimizing solutions (Figure 2.3).

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

Figure 2.2 NGSS's Eight Practices of Science and Engineering (NGSS Lead States, 2013, p. 48)

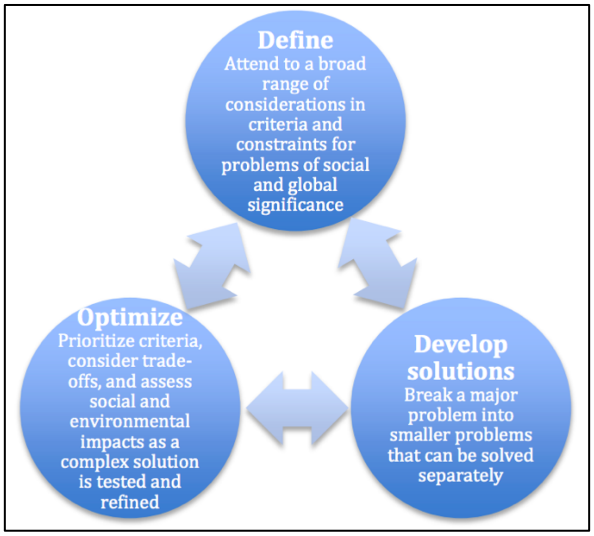

Figure 2.3 The NGSS Engineering Design Model for Grades 9-12 (NGSS Lead States, 2013, p. 106) Courtesy of The National Academies Press.

This NGSS model (the eight practices plus the triangle) is a great way to understand the interconnectedness of engineering design processes, but it is unwieldy for classroom use. As a list, there is a danger that the eight practices could be enacted as eight steps, which would undermine the iterative, flexible nature of engineering design and do the same negative work that the "scientific method" has been critiqued for, i.e., it oversimplifies a complex process and decreases the awareness of the involvement of reflexive human decision-making in scientific practice (National Research Council (U.S.), 2012).

Appendix F of the NGSS (NGSS Lead States, 2013b) defines the practices, but does not clearly relate the practices to more general "characteristic steps that must be undertaken" in an iterative system (National Research Council (U.S.), 2012, p. 46). This is intentional, as the design process is not so simple. The *Framework* (National Research Council (U.S.), 2012) states, "In reality, scientists and engineers move, fluidly and iteratively, back and forth among these three spheres of activity [those in Figure 2.3], and they conduct activities that might involve two or even all three of the modes at once" (p. 46).

For a novice engineering teacher this might seem like confusing guidance. Though the NGSS is not curriculum or teaching methods, a teacher might still try to glean pedagogical advice from it, and the list of practices (labeled with sequential numbers) seems to be a fairly straightforward approach. She might think, "Yes, I can do these one after another and do engineering design." Then, that teacher might find the three-step cycle in NGSS Appendix F (NGSS Lead States, 2013b) and wonder, "Which practice goes where?" If she assigns the practices to the headings in the diagram, she might still go through the practices "in order" anyway, or she might wonder where to start and where to end. Lastly, if she follows the trail back to the *Framework* (National Research Council (U.S.), 2012), she might read that engineers could be doing one, two, or three aspects of engineering design at once. She might wonder what that looks like, and how that relates to the practices from NGSS.

I believe this could be overwhelming for teachers inexperienced in engineering design, and indeed I have heard in workshops and at NSTA conferences that teachers "don't know where to start" with engineering design. The NGSS and *Framework* described the complex realities of the engineering industry, but at the same time overly simplified engineering design practices in the concrete recommendations made to teachers via the NGSS practices.

A four-phase model of the engineering design process was developed by high-school mathematics and science teachers affiliated with the Knowles Science Teaching Foundation (KSTF) (Johnson, Murphy, O'Hara, & Shirey, 2015). Figure 2.4 shows their model, in which four overlapping circles, represent "phases" of the engineering design process: problem definition, design exploration, design optimization, and design communication. Each phase is considered an iterative cycle in itself, and the whole system is one of iteration as well. The circles are overlaid on a diamond to represent "design as…an iterative loop of divergent-convergent thinking" (Dym et. al, 2005, p. 104), i.e., expansive ideation followed by narrowing down on one solution. The overlap of the circles implies that the designer can move back and forth between the phases even after a final design decision has been made and communicated.

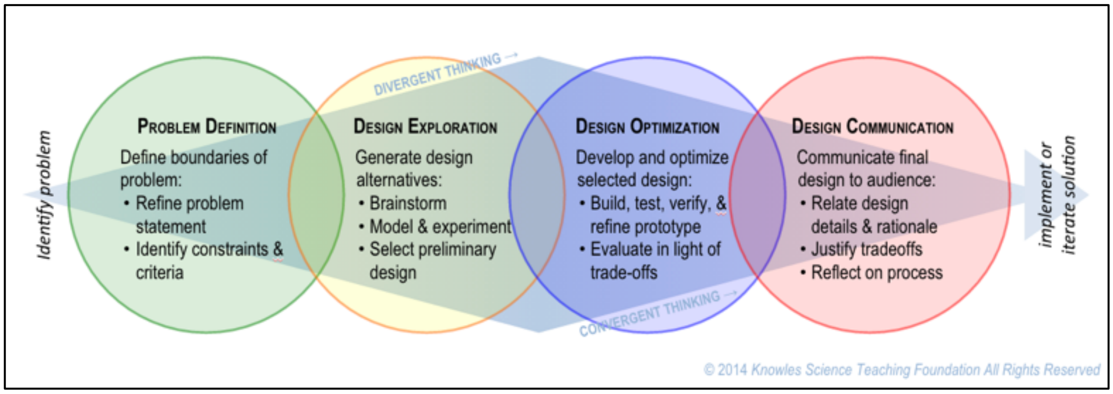

Figure 2.4 The KSTF Four-Phase Engineering Design Process Model (Johnson et al., 2015, p. 19)

The four-phase KSTF model is a pedagogical tool intended for use in a broader package of professional development to help high-school teachers begin to integrate engineering design into their instruction. In contrast, the NGSS treatment is more of a philosophical statement, or definition of what engineering design is, instead of a practical model for classroom use.

The overall features of the four-phase KSTF model and its specifics are intentional and meant to help guide practical use. The graphic design is intended to show the overlapping phases by literally overlapping the circles. Actions listed within the phases are not sequentially numbered, implying they may be done in any order. The shape of the background diamond is intended to underscore the labeled divergent and convergent aspects of the overall design approach. Each phase of the four-phase engineering design process in Figure 2.4 involves particular actions. By specifying these now, I can use the model in the classroom as a framework to identify actions associated with engineering design. In fact, this is the language we used in the classes at Merlin, so the teachers' actions may be described by these terms.

In the problem definition phase, a problem statement is refined to describe the problem, the stakeholders, major criteria (an optimizable need of the design), real world and project-based constraints (absolute needs of a successful design), and the role of the designer. Because this process will be used in a classroom, not at a design firm where the client is the primary stakeholder, the stakeholders must be explicitly decided upon by the teacher or the student. This allows students to determine to whom their design must be accountable, or for the teacher to specify demands within the project.

In design exploration, students think divergently to generate design alternatives. Here the students direct their own actions, limited by the constraints of the challenge, not by the explicit instruction of the teacher, making this phase reorient the classroom to being more open-ended and student-centered (Johnson et al., 2015). Students may do initial modeling and experimenting (sometimes called rapid prototyping or tinkering) to generate multiple design ideas on the way to selecting one idea that they will test and refine through design optimization.

In a content science class, design optimization may look like a traditional experiment where the independent variable is continuous variations on one element of the design and the dependent variable is the measurements of the optimizable criterion. Depending on the needs of the design, students may need to learn how to do new kinds of tests; learn about new science content knowledge; practice or employ their own content knowledge; learn about problem solving by systematic design; and work on interpersonal, creative, organizational, and communication skills. Students must justify their design decisions with data gathered during optimization.

Students eventually present the optimized design to their stakeholder audience through the design communication phase. They must rationalize their design decisions, describing the data that informed their designs, and justifying any tradeoffs they made. To practice metacognition, students must reflect on the process of design in their communication.

Throughout all of these phases, a student or a class may chose to return to previous phases, moving left-to-right and right-to-left within the diagram. For instance, problems may be further refined after new constraints are identified in optimization, optimization experiments may lead to the need for more experiments, and communication may lead to the need for more tests. Depending on available time, a teacher might either plan for multiple rounds of optimization, scaffolding in the cyclical nature of the process, or allow it to happen naturally. In this way, the system's parts and the system as a whole are both iterative. Parts may be repeated, and the whole may be repeated from the beginning, even after finishing, to refine the problem and improve the design further.

The four-phase KSTF model is useful because it shows how the true complexity of engineering design can be responsibly simplified for classroom use. Thus, I believe the simplifications and representations in Figure 2.4 may be beneficial for teachers, but I am not implying that this model completely captures or replaces the full picture of professional engineering design.

2.2.3 The Four-Phase Model Provides Useful Structure

The four-phase KSTF model was created to help teachers actually start integrating engineering design, and the model suggests scaffolds to do so. It is intended that teachers have flexibility to use the phases independently while keeping their students' eyes on the big picture. The four phases may stand alone in practice, so that a teacher can scaffold the process in pieces. Accessing phases separately may reduce the time commitment of a teacher when trying to bring engineering design into a content classroom, but recognizing that the phases are rooted in the overall process is still important.

The four-phase KSTF model (Figure 2.4) seems to have a “start” and an “end” instead of being a continuous loop like the NGSS diagram (Figure 2.3). This is intentional, to provide teachers a more linear way of planning, but using this model requires that teachers be aware of how this is only a model of the complex, cyclical reality of design, even though they must actually start and end the process somewhere.

The four-phase model encompasses the NGSS’s eight scientific and engineering practices. Each practice is present in several phases, emphasizing that the practices do not stand alone as sequential steps. The practices are seen throughout the engineering design process even though the process is viewed as phases.

Both the NGSS and the four-phase model hit on many hallmarks of engineering design, but they are similar in their drawbacks because they are both just models. While the various steps that are present in each might seem to matter on the surface, a shift in the way we view the ontology of “designing” helps to overcome this discomfort. “Engineering design” does not live in either of these diagrams; it lives in the actions that even novice students do as they create an object to satisfy a need. Any diagram is insufficient at capturing “design thinking” because it is thinking.

In a way similar to how the Nature of Science movement insists students and teachers need to be explicit in acknowledging that classroom science is just a representation of professional laboratory science (McComas, Clough, & Almazroa, 1998), teachers and students need to recognize and be explicit about the limitations of any classroom model of engineering.

The NGSS stated that it is the iterative cycle of engineering design that “offers the greatest potential for applying science knowledge in the classroom and engaging in engineering practices” (National Research Council (U.S.), 2012, p. 201), but my history with engineering and science has convinced me that doing engineering design can also teach science content, not just provide a vehicle for applying (practicing) content knowledge. While I agree that doing engineering design can help students engage in engineering practices and teach engineering design as a problem-solving method, the *Framework* misses other benefits of learning engineering design such as enhancing collaborative, communicative, creative, and metacognitive skills, values, and interests. The four-phase KSTF model encompasses the divergent-convergent aspects of creative thinking and brainstorming and places emphasis on communication to elevate the softer skills associated with sharing a designed solution.

Neither the NGSS nor the KSTF model is better than the other; rather they offer different advantages and disadvantages. The NGSS (NGSS Lead States, 2013d) representation of engineering design is a philosophical statement about the need for engineering integration but was not meant for direct instructional guidance. The KSTF model (Johnson et al., 2015) was intended for teacher and classroom use, offering holistic and specific guidance for teachers, but it hasn’t been “tested” with teachers.

2.2.4 Using Inquiry and Engineering Design to Teach Science Content

In Chapters 4 and 5, I describe how the teachers in my study attempted engineering-design integration for two purposes: to teach students about engineering design, and to teach students new physics content. To understand their methods, it is necessary to explore how their regular instruction relates to scientific inquiry and "inquiry instruction."

In inquiry instruction, students "use scientific reasoning and critical thinking to develop their understanding of science" (National Research Council, 1996, p. 105). Students do science to learn science, instead of learning and *then* doing. In this method, teachers must provide opportunities for students to reason up to an instructional goal instead of just telling students the instructional goal. For instance, instead of just telling the students that force is directly related to the distance you pull a spring from equilibrium, the teacher might provide opportunities for students to see how force is related to displacement and hope they reason the relationship, or might help them gather and graph data to find the mathematical relationship from the graphical representation.

"Levels of inquiry" can describe how much a teacher helps guide the students. "Open inquiry" (Rezba, Auldridge, Rhea, & The Virginia Department of Education Office of Elementary and Middle School Instructional Services, 1998) or "Level 4 inquiry" (Bell, Smetana, & Binns, 2005) involves the least direction from the teacher or teaching materials (see Figure 2.5). The student devises his or her own research question and methods, and finds a solution without having been told what to expect.

The teacher might suggest, “Investigate this pendulum,” but doesn’t provide a research question. “Confirmation inquiry” or “Level 1 inquiry” is more like a typical lab in high school; after a lecture on a physical relationship or concept, the students receive a laboratory question to answer and a procedure to use to answer the question. The students already know what relationship they should find based on the lecture. In between open (level 4) and confirmation (level 1) are “guided inquiry” (level 3) and “structured inquiry” (level 2).

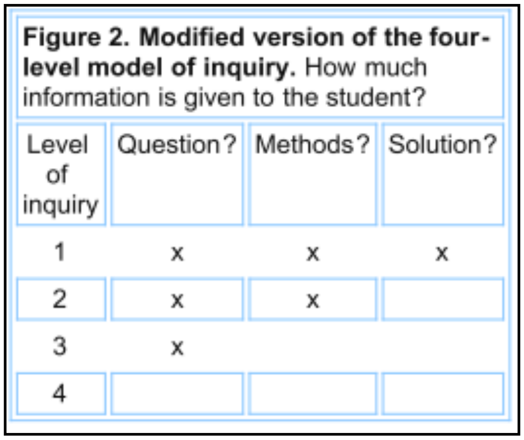

Figure 2. Modified version of the four-level model of inquiry. How much information is given to the student?

Level of inquiry	Question?	Methods?	Solution?
1	x	x	x
2	x	x	
3	x		
4			

Figure 2.5 Levels of Inquiry (Bell et al., 2005, p.32)

Any level of inquiry could be used in engineering design, but not knowing what the effect of changing a variable would have on the design’s performance means that engineering design to investigate a variable is at least level 2, structured inquiry. How much guidance the teacher gives as far as procedures and research questions within the engineering design experience can alter the level of inquiry embedded in the engineering design challenge.

If the challenge of helping students learn science content while simultaneously learning about the processes of inquiry is analogous to the challenge of helping students learn science content while simultaneously learning about the processes of engineering design, then we might expect issues in engineering-design reform implementation to be similar to issues that were and are present in inquiry reform implementation.

2.3 Historical Science Teaching Reform Implementation Issues

Major national science-education reform has swept over the United States' classrooms at least four times in the last half century. Teachers have been asked to adopt curriculum, methods of instruction, and beliefs about science education that aligned to the reform efforts (Czerniak & Lumpe, 1996); and research suggests several issues that may arise when reform is implemented. Forty states have expressed interest in adopting the NGSS. As of February 2016, 17 states and the District of Columbia have adopted them (National Science Teachers Association, n.d.), and 41 total states have some engineering standards in their state's school science standards (Kersten, 2013).

This means that science teachers with a broad range of science and engineering backgrounds will need to bring engineering design into classrooms as never before. Looking at elements that aid and hinder reform implementation could help smooth the transition for teachers integrating engineering design now.

2.3.1 Successful Reform Implementation

Teacher implementers construct ideas about reform from policy, which influence what they do (and do not do) when implementing the reform. Previous waves of reform suggest that schools and school districts will form teams of teachers charged with creating lessons to bring engineering into science classrooms. Research has shown that these development groups are most productive when teachers' collaboration is situated within school contexts and acknowledges teachers' own practice, experience, and culture (Desimone et al., 2002; Laferrière, Lamon, & Chan, 2006).

Professional development (PD) is the dominant tool for changing teaching methods (Smylie, 1996). Research has found that successful PD involves sustained duration, a focus on content-matter learning for teachers, and coherence with school, district, and state objectives (Desimone et al., 2002; Supovitz & Turner, 2000); collective participation within professional groups situated in schools (Lieberman, 1995; Supovitz & Turner, 2000); curricular-grouped environments (Wayne, Yoon, Zhu, Cronen, & Garet, 2008); and "opportunities for teachers to actively interact and engage with each other around curriculum and instruction" (Desimone, Smith, & Phillips, 2007, p. 1008).

Elsewhere, research has shown that successful reform implementation was supported by teacher articulation and reflective examination of underlying disciplinary learning goals and associated epistemological assumptions (Laferrière et al., 2006). In working groups, teachers' shared values and visions were significant indicators of working-group success (Stoll, Bolam, Mcmahon, & Wallace, 2006).

Understanding issues that arose in other science reform movements like inquiry-learning reform, nature-of-science reform, and project-based learning can help us understand what to watch for during the introduction of engineering design in the NGSS reform.

2.3.2 Inquiry Instruction Reform Never Got a Solid Root

Previous inquiry-oriented reform emphasized "hands-on" and "discovery learning" scientific inquiry. However, the Deweyan Project Method in the mid-20th Century and the National Science Education Standards met similar issues with inquiry integration and teacher epistemology alignment (R. D. Anderson, 2002). Though reform materials were widely used (R. D. Anderson, 2002; DeBoer, 1991; Stake & Easley, 1978) and "considerable time and effort" (Czerniak & Lumpe, 1996, p. 251) was spent by national and local organizations to train teachers for reform implementation—including via professional development, curriculum and course development, informal science education, and undergraduate education (Czerniak & Lumpe, 1996)—research revealed that teachers were not universally using the student-centered, inquiry-teaching techniques described in the reforms. The materials were not used in ways that were consistent with the "philosophy" of inquiry teaching (R. D. Anderson, 2002, p. 7) in either case. In the case of the Project method, students frequently continued to learn science through memorization and not through inquiry

(C. W. Anderson, Holland, & Palincsar, 1997), as high school remained primarily preparatory for college (DeBoer, 1991).

During the 1900s and early 2000s, difficulties with inquiry included “a widespread philosophic persuasion in favor of textbooks” (R. D. Anderson, 2002, p. 7) and other contextual teaching factors limiting teachers’ understanding of and commitment to inquiry teaching (Krajcik, Blumenfeld, Marx, & Soloway, 1994).

R. D. Anderson (2002) characterized the problems of inquiry reform implementation along three dimensions—technical, political, and cultural—concluding that the task of inquiry-based reform was much bigger than technical matters such as in-service training or curriculum distribution. Indeed, other researchers speculated that a general lack of commonly accepted definitions of the constituent elements of inquiry impeded attempts to instill the idea that science should be taught through inquiry (Abd-El-Khalick et al., 2004; National Research Council (U.S.), 2012), which points to an issue of science education epistemology.

2.3.3 Epistemological “Dilemmas” in Science Education Reform

There are internal struggles “including beliefs and values related to students, teaching, and the purposes of education” (R. D. Anderson, 2002, p. 7) that a teacher will encounter when shifting from traditional pedagogy to reform pedagogy, such as the role of the teacher (as coach or facilitator instead of dispenser of knowledge), the role of the student (as self-directed learner instead of passive receiver), and the role of student work (student-directed learning instead of teacher-prescribed activities). R. D.

Anderson (2002) called these internal discomforts “dilemmas” to separate them from external impediments commonly called “obstacles” or “roadblocks.”

Inquiry required teachers to adjust their usual assumptions about the validity and limits of science knowledge. In one sense, teachers now had to include the process of doing science in the scope of what school science knowledge includes. School science was no longer just facts in a textbook; the teacher was also responsible for students learning an authentic research practice. In this sense, the dilemma is epistemic—just what *is* science must change, and that may be uncomfortable or nearly impossible if not adequately recognized and addressed (R. D. Anderson, 2002).

In another sense, inquiry integration forced teachers to reckon with how science knowledge was taught and learned. That is, do students learn by absorbing knowledge through direct instruction (lecturing) and direct observation (such as in a clear-cut, confirmation lab), or do students learn by active sense making, such as in an inquiry experiment before instruction? From this perspective, the lack of fidelity in inquiry integration could have been an epistemological issue.

Epistemology is “the nature of knowledge, its possibility, scope, and general basis” (Hamlyn, 1995, p. 242). How an individual thinks about learning is affected by social and personal beliefs and understandings about learning (Greeno, 1989) and by the way the individual’s epistemologies of learning are connected to patterns in learning (Belenky, Clinchy, Goldberger, & Tarule, 1986; Dweck & Leggett, 1988). Hence, R. D. Anderson’s (2002) dilemma is a situation in which the reform epistemology challenged a teacher's existing epistemology. For instance, learning is when I transmit knowledge to a student, versus the reform-minded version where learning is when students fabricate knowledge. Teachers might have had an internal epistemological struggle with the limits of scientific knowledge and how to teach science.

A transmissionist epistemological stance might make it harder to conceive of a student building their own understanding of science knowledge through active sense-making, and could reduce the possibility of a teacher valuing student sense-making over direct instruction.

2.3.4 Epistemological "Dilemmas" in Nature of Science Reform

The 1990s nature of science movement followed social constructionism advances by recognizing that scientific knowledge was a social and human construct. However, not all teachers took up this shift. The NSES (National Research Council, 1996) included history- and nature-of-science standards at each grade level, including the socially-constructed nature of science ("science as a human endeavor"), the tentative nature of science ("change and continuity are persistent features of science"), and the contextual nature of science ("new ideas in science are limited by the context in which they are conceived" (p. 13)). However, C. W. Anderson et al. (1997) found that school curriculum did not present a shifted understanding of the nature of science. Practitioners more often clung to the objectivist view that science was "specific knowledge of vocabulary and facts" (R. D. Anderson, 2002, p. 6).

Duschl and Wright (1989) found that teachers paid little mind to the nature and role of theories in science.

R. D. Anderson (2002) claimed that this was also an epistemic dilemma, and further, that it was possible to avoid the discussion of the epistemology of science because both sides of the epistemic debate agreed that the point of science teaching was introducing pupils to “the accepted science view of the world” (Driver, Squires, Rushworth, & Wood-Robinson, 1994, p. 10). Brickhouse (1990) found that teachers’ epistemologies, even when unexplored personally, remain consistent in discussion and practice and are translated through their instruction to students.

2.3.5 Epistemic Issues in Project-Based Science Education Reform

Project-based science gained popularity in the 1990s in response to the observation that students were not deeply learning science even though they were passing many consecutive years of science classes (Ladewski, Krajcik, & Harvey, 1994). Project-based science, also called project-based learning, was a type of reform-minded, inquiry teaching centered on constructionist epistemologies of learning. It consisted of posing real-world, contextual questions that encouraged students to engage in scientific investigation while they answered the question and created artifacts to reflect their solutions (Ladewski et al., 1994). Advocates believed students could develop deeper understanding of science and take ownership of their learning through project-based learning (Ladewski et al., 1994).

Ladewski, Krajcik, and Harvey (1994) investigated a middle-school science teacher's first uses of project-based science and found that the teacher, Connie, struggled with epistemological dilemmas. The authors found Connie's "previous beliefs about teaching and learning came into conflict with her emerging understanding of the premises underlying project-based instruction" (p. 499). Before the project-based unit in the study, Connie believed her primary goal, as a science teacher, was to cover the content she was assigned to teach. She saw "hands-on" prescriptive laboratory activities and student-centered laboratory "investigations" as "enhancements" to learning instead of an "integral component" (p. 500).

During two project-based units, the researchers identified two epistemological dilemmas. The first related to the epistemology of science, or what the limits and scope of science were. Connie had trouble valuing student exploration and investigation in the project-based units because she still saw "science as a set of correct answers" (Ladewski et al., 1994, p. 508). She wanted to be sure that students would learn the right stuff, and she undervalued students learning about science as an inquiry process. This dilemma arose because Connie did not recognize "the contradictions between certain of her old beliefs about teaching and learning and the underlying constructivist premises of project-based science" (p. 507-508).

The second dilemma also related to students constructing knowledge, but was more tethered to the systems of power in science class. Project-based learning emphasizes student collaboration and investigation to create new knowledge, but practices of creating knowledge through group work disagreed with Connie's "view of teacher as content expert and director of classroom activities" (Ladewski et al., 1994, p. 508). Again, Connie's previous epistemology of science teaching clashed with the reform's epistemological assumption that students could and should guide their own learning.

The study followed Connie through iterative cycles of teaching, collaboration, and reflection and found that, through direct video confrontation and direct questioning about her internal "dilemmas," Connie was able to overcome some of her preferences for content science and teacher-centeredness. She benefitted from a supportive environment and the adoption of aligned "warranted practices that derive from a teacher's understanding of the theoretical premises of an instructional approach" (Ladewski et al., 1994, p. 514). Such warranted practices could support reform effort implementation while considering a teacher's background and classroom context.

2.3.6 Educational Reform in the 2000s

In recent years, research in the learning sciences, brain-based research, and equity-oriented education research have increased emphases on students' complex physical, psychological, developmental, and cultural needs (Hamos, 2006), which has given rise to differentiation reform and culturally responsive pedagogy. Differentiation was marketed as an opportunity to meet every individual student's readiness, interests, and learning-preference needs by focusing on student choice and instructional tailoring (Tomlinson, 2003). Differentiation met the need for unique instruction raised by brain-based research but was criticized for the enormity of time and resources necessary for planning and managing differentiated instruction (Simpson & Ure, 1994).

Culturally relevant pedagogy emerged in the 1990s (Ladson-Billings, 1994) as a "pedagogy that [empowers] students intellectually, socially, emotionally, and politically by using cultural referents to impart knowledge, skills, and attitudes" (Young, 2010, p. 248). But research found that exhibiting cultural competence or "utilizing the knowledge and experiences of minority students to bridge the entrance into the dominant society" (p. 252) was difficult to describe and difficult for teachers to enact, at least in part because of epistemological dilemmas; culturally relevant pedagogy requires teachers to see student cultures and interests as necessary and useful for building upon in designing and implementing instruction (Ladson-Billings, 1995), presupposing a constructivist stance toward learning. (To be clear, other dilemmas, including ideological dilemmas, no doubt also contribute to teachers' troubles with culturally relevant teaching.)

After the No Child Left Behind (NCLB) Act of 2001 placed assessment in the forefront of all aspects of education (Bybee, 2006), states were required to develop and deploy state standards and assessments. By 2010, the locally decided domains of "policies, programs and practices" (p. 22) created by every state were inconsistent and in need of guidance. The National Research Council (NRC) published *A Framework for K-12 Science Education* (2012), which described a new way to view science curriculum by way of practices, crosscutting concepts, and core ideas.

The NGSS (NGSS Lead States, 2013d) operationalized the NRC's *Framework* and described the ways that teachers could approach disciplinary core ideas, including engineering and technology, in relation to science and engineering practices and crosscutting concepts. The success of the NGSS inclusion of engineering design has not yet been studied at length, but if history is our guide, teacher epistemic alignment may play a role in the adoption and success of the NGSS engineering integration reform effort.

2.4 Expected Difficulties of K-12 Engineering-Design Integration

Daugherty and Custer (2012) listed primary challenges of engineering integration: "to identify a slot in the curriculum to house engineering; to identify a body of content; to convince policy makers, school administrators, and parents of the importance of engineering education; and to prepare teachers to effectively convey engineering content and concepts" (p. 18). As fewer than 5% of elementary teachers and fewer than 10% of middle- and high-school science teachers feel "very well prepared" to teach engineering concepts (Banilower et al., 2013, p. 24-26), teachers will need to "substantial[ly] change in both content and approach" (Daugherty and Custer, 2012, p. 19), including learning more mathematics and science, working with colleagues in other disciplines, rethinking and repackaging traditional content, rethinking teaching methods and learning, and using hands-on, open-ended design challenges.

Expected issues in integration include teacher deficit thinking about their students' ability to handle the demanding complexity of engineering-design instruction. A survey of 522 K-12 teachers by the American Society for Engineering Education (ASEE) found that though a majority of teachers had a positive attitude toward the impact and classroom potential of engineering integration, they were overall pessimistic about the potential of their students to access and succeed at engineering (Douglas, Iversen, & Kalyandurg, 2004).

Time and resources were cited as impediments to implementation, which led to a recommendation that science, mathematics, writing, reading, technology, and history be integrated in novel interdisciplinary ways into existing curriculum to reduce the time required to plan engineering lessons (Douglas, Iversen, & Kalyandurg, 2004).

By studying PD on engineering instruction, Daugherty and Custer (2012) and the National Center for Engineering and Technology Education (2009), found that teachers across a spectrum of PD expressed concerns about time, materials, and curriculum availability. Those researchers' work also identified systemic issues that need to be resolved to ensure engineering-design integration success, including identifying a purpose for engineering integration, establishing the intended audience of students (i.e. whether it is best for all students or just the select few), connecting a conceptual base and content within PD activities, and placing engineering and engineering design within the mainstream school curriculum (National Center for Engineering and Technology Education et al., 2009).

PD for current teachers will be important for shifting practices, and pre-service teacher training will also be required. “Significant changes” in preparation will need to address “important issues” of engineering integration, including adding “requirements for mathematics and science, core engineering content, curriculum and activity development, unique pedagogical demands of teaching engineering and appropriate collaboration with other STEM teachers” (Custer & Daugherty, 2009, p.23).

2.4.1 Expect Epistemic Difficulties with K-12 Engineering Integration

Since the publication of the *Framework,* various issues have been brought to light, including the clarity of the reform materials regarding K-12 engineering epistemology, teacher values and epistemology regarding engineering, and the types of instruction that engineering design will require of K-12 teachers. We should expect that teacher deficit thinking about the accessibility, complexity, and demands of engineering-design instruction, including time and resources (Douglas et al., 2004), will prove problematic for integration.

Chandler, Fontenot, and Tate (2011) wrote that a lack of cohesive standards for pre-college engineering knowledge and skills is evidence of how the “epistemology of engineering education has not evolved to specifically inform the exigencies of K- 12 education” (p. 40). Further, they claim that foundational documents such as the report *Engineering in K-12 Education* (Katehi et al., 2009) do not adequately address conceptual disconnections between how engineering is perceived and taught differently between the “K-12 classroom and generally accepted disciplinary perspectives and practices within the epistemic traditions of engineering education” (p. 42), including how the engineering profession and its practices are understood by the public.

To conform to the NGSS, science teachers need to teach engineering design in their science classes in an integrated way. This will require teachers to have some idea of what engineering-design teaching and learning means, and they will have to agree that it belongs in the science classroom and feel they have “room” for it. These are partly epistemic issues. The inclusion of engineering design and the recognition of contributions to engineering and technology from non-European civilizations as part of school science were intended to be a seismic shift in the boundaries of science curriculum, “redefin[ing] the epistemology of science or what counts as science, which in turn, defines or determines school science curriculum” (NGSS Lead States, 2013, p. 29). Teachers may grapple with whether these changes are disruptive to what and how they have previously taught if they face an epistemic mismatch with the notion of what is science and appropriate science content, if they simply don’t feel they have the time within their school year to add anything, or if they lack necessary resources for integration (Douglas et al., 2004).

Additional issues with engineering-design integration seem like reminders of known research. The NGSS assumes engineering design is the hallmark engineering process and requires that students do engineering design. However, the elements of engineering design—cycles of problem definition, design exploration, design optimization, and design communication (Johnson et al., 2015)—require that students engage in student-centered, student-decision-driven modes of learning, exactly the modes of learning that surfaced as epistemic "dilemmas" for inquiry, nature of science, and problem-based-learning reform teachers.

Research on engineering design as recommended by the *Framework* and the NGSS is required to understand just how teachers approach the adoption of these standards and practices.

2.5 Recommendations for K-12 Engineering Integration in Science

The NGSS is neither pedagogy nor curriculum, so what a teacher is actually supposed to do in the classroom may seem undefined. Luckily there are other recommendations, both general and specific, for how to integrate engineering into the K-12 grades. In the K-12 sphere, engineering should encourage curiosity, creativity, organization and logic, clear and concise problem formulation, focused decision-making, knowledge of mathematics and science, technical and practical knowledge, teamwork and communication skills, and the use of an engineering design process for doing engineering design or redesign, as well as for learning engineering concepts (Brophy et al., 2008; Truesdell, 2014). "[An] understanding of engineering practices can develop as they are used in the classroom to help students acquire and apply science knowledge" (National Research Council (U.S.), 2012, p. 201). So how should that look?

General K-12 engineering instruction recommendations suggest teachers should use engineering design for standards-based, interdisciplinary, student-centered pedagogies, such as "hands-on learning" described as "less theory-based and more context-based; for improving conceptions of engineers and engineering (Moore et al., 2013) emphasizing the social good of engineering and demonstrating how it is relevant to the real world" (Douglas et al., 2004, p.2) or relationships between issues, solutions, and impacts (Moore et al., 2013); for working to "Make Engineers 'Cool' " by initiating more aggressive outreach to urban school and girls, creating role models, mentors, and partnerships to attract these and other communities (Douglas et al., 2004); for emphasizing teamwork and collaboration (Douglas et al., 2004; Moore et al., 2013); for emphasizing engineering thinking including metacognition and ethics; and for utilizing engineering tools, techniques, and processes, including applications of science, engineering, and mathematics knowledge, and communication (Moore et al., 2013).

These strategies are intended to try to heighten the profile of engineering design in high-school students' lives, but they are slightly orthogonal to helping students understand the engineering design process. Next, let's look at recommendations for actually teaching students the engineering design process.

What should a teacher actually do to help students learn engineering design and learn with engineering design? The *Framework* (National Research Council (U.S.), 2012) assumes that inductive learning has a positive impact, and so, by providing opportunities for engineering design, students will learn the process of engineering design and learn scientific concepts. Hence, teachers must have students actually design to learn scientific concepts. The overarching recommendation for K-12 students to try the design process aligns with the need for engineering-design courses in higher education; lecturing on the process would be inadequate to describe the complexities that present themselves in the process. But teaching by the constructivist inductive teaching method may prove difficult in many of the same ways that teaching content by constructivist scientific inquiry was difficult.

Simple models of engineering-design instruction for K-12 education emphasize data-driven decision-making to meet a client's needs within a real-world system, considering various stakeholders, and defining problems. Students should think widely about how to solve the problem, choose and build one possible solution, test and iterate the solution based on quantitative data collected in the classroom laboratory, and eventually present the solution so that it may be put to use or trigger a redefinition of the problem for a more appropriate solution (Dym et al., 2005; Moore et al., 2013; National Research Council (U.S.), 2012; NGSS Lead States, 2013d).

Other specific instructional recommendations for K-12 engineering instruction include:

- using the NGSS science and engineering practices (Truesdell, 2014) or other processes of design (Moore et al., 2013);
- having the teacher act as the client;
- providing an informative client brief that plays up roles and motivates engagement in real-world applications and contexts;

- providing rubrics for student evaluation at the outset;
- requiring student voice in problem definition by having students restate the problem in their own words;
- teaching “rules of brainstorming” (Truesdell, 2014, p. 31) such as quantity of ideas over quality of ideas;
- employing teacher check-ins;
- providing deadlines but being flexible in time needed;
- keeping a work log and assigning frequent (daily) pieces of formative assessment including sketching;
- setting constraints via materials lists;
- using engineering decision tools such as pairwise comparison charts and decision matrices; and
- actually building the design (especially when construction is simple) (Moore et al., 2013; Truesdell, 2014).

These specific recommendations do not describe a very authentic engineering design experience; although providing a detailed and contextual premise is certainly important to creating the illusion of a design need, it sets up an artificial purpose for the design and sets artificial, elementary parameters for what is adequate, perpetuating a simplistic model of engineering design.

These recommendations also do not clearly relate the design process to learning science content. A content-minded teacher might wonder, “Where is the science instruction?” Many of the specific recommendations, such as teacher check-ins, flexible and responsive deadlines, rubrics, and work logs, are just good classroom management and might not be obviously significant for engineering design. Also, using these techniques in normal ways might be counterproductive. Using special engineering tools seems more significant, but using them is neither necessary nor sufficient for doing engineering design.

In sum, these recommendations do not seem fully adequate to describe what engineering design might look or feel like. To provide a sense of that, I will now diverge from this literature-based review of practices and recommendations to describe a form of instruction that seems more appropriate for inductive engineering-design instruction, where an engineering design challenge provides an opportunity to learn about the design process and to learn new physics content.

2.5.1 An Instructional Daydream

To establish an engineering-design context, one would expect to see the challenge, a real-world problem, posed by the teacher, who plays the role of "client," to students, who play the role of "engineer." If this takes place in a physics class, the teacher might hope that the students are going to learn about a particular physical phenomenon and have set up the problem so that the students must test their design in a way that identifies a physical relationship. This is tricky to do; creating a contextual need for some new or revised product that could be made in many different ways, while also expecting that every possible way will require a student to learn some specific physics content, might mean that the posed problem and associated design tests must be more individually scaffolded and guided than is possible for a single teacher in a classroom.

Conversely, if a teacher wanted to absolutely maximize the authenticity of designer decisions in the engineering-design challenge, it might not be possible to target specific learning content. Here, I will play out the former case, for a more specific learning goal, and remark that more research needs to be done on how scaffolding of the engineering design process (including problem definition, design exploration, and design optimization) may be inversely related to the ability to target specific content goals.

To get students started on a problem, the teacher might first create space and time for them to explore the problem in groups and without teacher intervention. The students would likely do a lot of problem-definition work at this stage, such as describing assumptions, givens, questions, and needed research, before they could articulate the problem fully in their own words to demonstrate an understanding of the initial constraints of the problem space and the criteria they will optimize.

The teacher as "client" could remind students of what is known about the problem already, and the teacher as the "instructor" could provide resources (material data sheets, measurement tools, laboratory materials). Ideally, however, the teacher would not participate as an "engineering team member," so that the students would define the problem themselves.

Once the problem is defined, and even as it's being defined, students might be thinking about what could work to solve the problem and, ideally, keep track of their ideas via sketches or some kind of written document. (The National Academies of Engineering (NAE) and NRC stress that sketches are significant in idea organization and enumeration). As certain ideas come together in the abstract, they might also come together in physical models, with constant critique of ideas against the definition of the problem space. The teacher might ask students quasi-mechanistic prompts here to encourage students to make sense of the underlying mechanistic science within the design space.

In engineering design, it is good to have many ideas, and it would be tempting for a teacher to require an arbitrary minimum number of generated ideas. However, in this space the teacher should emphasize the benefits of generating many ideas but not demand a minimum number. If students are motivated to solve the problem the best that they can, then the teacher might remind them that generating more ideas will allow them to think wider and more productively. This could be more motivating for solving the problem than an arbitrary mandate for ideas.

While students are generating ideas, they might try out some of them by tinkering, playing with materials, or rapid prototyping. When materials are needed, the teacher could provide resources as much as is reasonable for that school, context, or spread of days. At this point in the engineering design process, the teacher is monitoring students, pressing students to justify their decisions in light of the constraints and chosen criteria, asking students to track the development of their ideas and solutions over time, and pushing students to create tests for designs as they are being invented.

Checking in as a teacher at this stage requires resisting offering judgment and avoiding making contributions towards the design. If the design is truly for a client, and that client is not the teacher, then the teacher's natural authority in the class might disrupt the delicate role-play the students are in. After all, they may be invested in the context of the problem, but they are still in school and the teacher is still an authority whose opinion could sway the creative design process away from student ideation. Still, the teacher isn't impotent and can offer supports for prioritizing criteria (such as a pairwise comparison charts), for thinking about stakeholders (conferences or Skype calls with a client), or for planning future design actions (knows, need-to-knows, next steps, design models, or brainstorming effective testing).

Eventually, the students might arrive at one best design idea, and need to test it, improve it, and generally optimize it. If an inquiry-instruction-like approach is followed, then students could design testing experiments as needed to inquire about the design's success. Knowing that there are many dimensions of testable variables for any given phenomenon and object, naming and negotiating the multi-variable problem could be challenging for students (and adults) (NAE and NRC, 2009). The teacher could remind students of the need for appropriate variable management and data collection, ideally already normalized in inquiry practices.

If the teacher has a physics agenda, the presence of various lab materials and technical documents that describe their use can be suggestive, just like they can be in open-inquiry instruction. But since given materials can be suggestive, the teacher might try to remain clever in not telegraphing his or her intentions too much and not limiting students by suggesting a narrow solution.

All appropriate scientific inquiry conventions would still need to be followed, and students would gather enough data to draw conclusions and defend against random error, testing extremes and limits to confirm their conclusions, and then would use the data to identify strengths and weaknesses in their designs. Throughout the testing phase, the teacher might be rather hands-off, but that assumes students already know how to scaffold an investigation into some element in their design. The teacher could act as a technical lab consultant or build in peer check-ins, group critiques, or preliminary results-sharing sessions to give the students feedback without having teacher authority interrupt their group dynamic.

After testing, if the students want to revise their product design, expectations, or criteria, or do more research, or even change their constraints, then they should be encouraged to validate the change by testing their solution again. To effectively emulate engineering design, the students need the space and time to make adjustments and retest before finalizing a design recommendation or product. Time management is the teacher's responsibility. Here, the teacher could either provide adequate time to improve the designs, could cut off the design cycle and say "just give me what you've got," or ask for future steps, an "if you had more time" approach. But regardless of when the teacher decides to end it, the expectation for completion should have been made clear as an initial constraint.

Students are required to show mastery of subject matter in school, and this engineering design challenge should be no exception. Students should be asked to show mastery of their thinking and designing processes by presenting some representation—such as a prototype, model, or sketch—of their final design; by justifying the design's components—such as structure, function, and materials—in light of the criteria or purpose desired; and by defending tradeoffs involving factors such as cost, impact, waste, and risks. A client, and the teacher, would likely want to see evidence of how students metacognitively thought about their own thinking during the project.

Over and over in this scenario, what the teacher does can affect the student's actions. I have pointed out places some where the teacher's actions can scaffold student thinking and processing and where teachers should be wary of hindering student thinking and processing.

Physics classes seem like a good place to start integrating engineering design. Current physics teachers are more likely than other science teachers to have training in engineering; 28% of physics teacher have taken at least one engineering course compared to only 10% of all other science teachers (Banilower, 2013). But little research has been done on the ways that physics teachers utilize engineering design in their physics instruction.

2.6 Little Research on K-12 Engineering Integration

K-12 engineering education is a relatively unexplored field in science-education research and in engineering-education research. Major complaints from the NAE and NRC include the fact that research on engineering instruction of K-12 students is commonly based in opt-in programs, and more often studies "enjoyment" than conceptual or specific engineering learning gains (Katehi et al., 2009, p. 63). With only a handful of engineering education research groups operating in the U.S. compared to hundreds of science-education or mathematics-education research groups, no wonder the NAE and NRC (Katehi et al., 2009) reported a dearth of student data.

But it's not just student data that is largely under-researched; there are few studies on teachers teaching engineering design, on teacher pedagogy for engineering-design instruction, or on PD for engineering-design integration. Indeed, even the NAE and NRC (Katehi et al., 2009) reviewed 44 different packaged K-12 engineering curricula but did not directly observe engineering PD or teaching due to time constraints. My study will contribute to filling that observation gap in current research on engineering instruction in K-12 science classes (Katehi et al., 2009).

2.6.1 Fear and Cognitive Load Impede Engineering in K-12 PD

So what problems might come up in engineering-integration PD? Studies have found that teachers unfamiliar with engineering design may feel "anxious and apprehensive" (Katehi et al., 2009, p. 112), and even feel terror (C. Cunningham, 2007), which “can inhibit the effectiveness of professional development programs” (Katehi et al., 2009, p. 112). Fear and other factors can contribute to teachers simply not wanting to participate in PD.

The open-ended nature of the engineering-design process itself might be uncomfortable, and maybe even ungraspable, if teachers are unable to “undo the mindset” that answers are either right or wrong (Benenson and Neujahr, 2007, as cited in Katehi et al., 2009, p. 112). Research in the vein of cognitive load theory (CLT) has found that juggling a large number of variables, as is necessary in most engineering contexts, can “easily overwhelm the limited cognitive resources of most individuals, adults or students,” (p. 129) but that cognitive structures, like the nature of causality, and the goal of testing, along with structural scaffolding (simplifying problems, “chunking,” and using external representation, etc.), can be taught to students and can help.

Some K-12 teachers learning a packaged engineering curriculum in PD had trouble understanding the science and (especially) the mathematics in the materials. More generally, not knowing what’s in the curricular program being presented, or what the learning progression is, can also interfere with PD effectiveness (Katehi et al., 2009).

2.6.2 Research on Engineering in High-School Physics

Physics might seem like a science with a high potential for successful engineering integration because mechanical physics concepts and mechanical engineering seem so closely related (Dare et al., 2014). However, only 28% of high-school physics teachers have completed an engineering course (Banilower, 2013, p.5).

Research on engineering integration in high-school physics teaching is slim, considering that there is considerably more evidence of the effect of engineering design and design-based instruction on students. Researched engineering curricula include stand-alone engineering kits and lessons in middle-school science (Schnittka, 2012; Schnittka & Richards, 2014), technology-enhanced integrated STEM units (Chiu & Linn, 2011), and engineering-design influenced STEM literacy gains and outcomes (Apedoe et al., 2008).

In one of the few studies on engineering-design instruction in high-school physics, Dare et al. (2014) studied teachers who attended a five-week intensive “physics + engineering” PD. The PD trained teachers on engineering integration so that they could enact it within high-school physical science courses. Three attending teachers then instructed an engineering design challenge that they had encountered in the PD in their high-school physics classes. The study found that when these teachers instructed the challenge for their students, the teachers dropped the physics content from the lesson, and instead focused only on modeling engineering design. Where physics content was included, it was as physics problems at the end of the accompanying packet.

In her dissertation study of high-school physics teachers, Kersten (2013) observed and evaluated three teachers’ engineering projects in high-school physics against the *Framework* (Moore et al., 2013) and found that all three were most successful at teaching processes of design and least successful at teaching conceptions of engineers and engineering; issues, solutions and impacts; and ethics portions of the *Framework*. Interviews revealed common concerns about time management and disparate motivations for teaching engineering design processes explicitly.

Roehrig and Moore (2012) found that using engineering design as a context to teach science frequently resulted in less than satisfactory design activities—such as tinkering, and trial-and-error—to solve a challenge, or missed opportunities to explicitly connect science content directly to the challenge. Using engineering design to effectively teach content requires doing engineering design and content instruction concurrently.

2.7 Teacher Decision Making Should be Explored

The Dare et al. (2014) study did not get into teacher beliefs, values, or epistemology to describe the decisions made by the three sample teachers, but it is widely agreed that teachers' beliefs about learning and instruction influence instructional practice and teacher decision-making (Borko & Shavelson, 1990; Nathan, Atwood, Prevost, Phelps, & Tran, 2011). Also, as outlined earlier, epistemological misalignments have been a cause of problems for multiple rounds of science education reform. Hence, my study goes into such problems and seeks the reasons, including epistemological reasons, for teachers' instructional choices.

Researchers have used many words to describe what makes teachers do what they do: premises (Ladewski et al., 1994), values underpinning epistemologies (Littledyke & Manolas, 2010), fundamental properties of thinking and learning influenced by beliefs and understandings (Greeno, 1989), values and beliefs (R. D. Anderson, 2002), beliefs and attitudes (Czerniak & Lumpe, 1996), epistemologies (R. D. Anderson, 2002), and sometimes combinations of all of these. For instance, R. D. Anderson (2002) switched between the use of “values and beliefs” and “epistemology” in his description of “dilemmas” (p. 7) without explicitly distinguishing between them. The point here is that all of these words describe theoretical constructs to explain reasoning, and all have some aspects of epistemology embedded within them as influences.

In this dissertation, I use the concept of “resources” to describe locally coherent patterns of thought and action that seem to affect teacher decisions, and this enables me to identify patterns of decision-making, including epistemological reasoning, in terms of recurring combinations of thoughts and actions. My use of “resources” here is different from other meanings of “resources” such as textbooks, written curriculum, lab equipment, or other classroom and teaching artifacts.

My conceptual framework for “resources” is near that of Hammer, who used “resources” in the sense of “resources [students] bring to learning.” “Resources” may be thought of as already existing, elemental or compound, and declarative or procedural, and, as they may be productive for learning, they may also be productive for teaching. They are of a finer grain size than beliefs and are sometimes described as analogous to diSessa's p-prims (Louca, Elby, Hammer, & Kagey, 2004).

I also use "resources" more broadly than either Hammer or Hammer and Elby. I am drawing on the idea of resources to enumerate bits of reasoning that are evidenced by locally coherent patterns of thought and action similar to Hammer's physicists "searching their knowledge and experience, trying out different ways of thinking" (D. Hammer, 2000, p. S52). Some resources emphasize actions, like skills, teaching practices, and well-practiced routines; and some emphasize thought, like mindsets, attitudes, and beliefs or epistemological stances. Separating out the ontology of how thought relates to action is not the point of the use of "resources" here, and I don't attempt to do that work. Instead, I use the term to categorize an intuitive sense that certain bits of reasoning conglomerate to guide thought and action, and these conglomerations are drawn upon variously in individual moments to influence teaching decisions when trying to bring engineering design into classroom instruction. Acknowledging and investigating resources in this way may be helpful for understanding the thinking and deciding that a teacher does. My use of resources as a unit of analysis is an assets-based approach and is counter to the deficit-based use of misconceptions in analysis.

In this resources framework, (1) teachers have repertoires of resources that are bigger than what you would see at any given time. (2) Resources get "called up" or activated in various combinations due to situational conditions in response to classroom, contextual, peer, or social contexts, and are not necessarily consistently called up every time. (3) Sometimes co-activated resources may be highly unstable, and sometimes they may be mutually reinforcing.

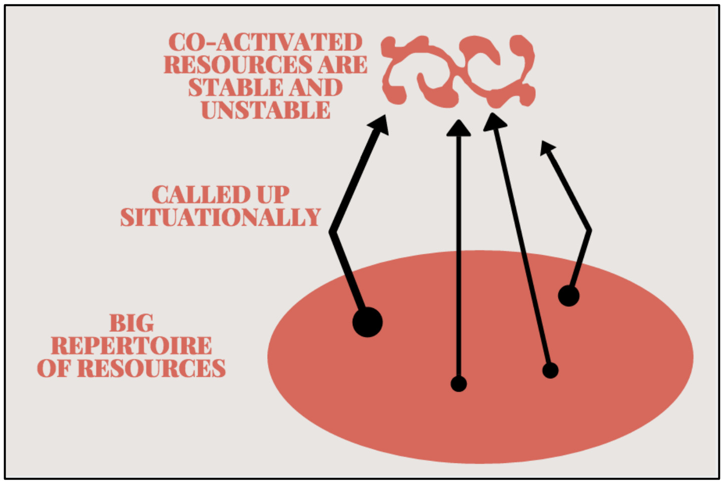

Figure 2.6 Three Aspects of the Resources Framework

Clearly, there can be lots of resources. This dissertation, focuses on resources affiliated with thoughts and actions, such as skills, well-practiced routines, content knowledge, comfort with content knowledge, and mental energy to take on changing things, as well as epistemological resources, such as what counts as knowledge, learning, and teaching in physics or engineering.

Sense-making and in-the-moment decisions are guided by combinations of these resources, like elements joining to make a particular molecule which itself may be locally coherent and stable, or be tenuously cohered or even in conflict with other resources at play. Resolving these conflicts may take mental effort and work (Hammer, 2000). Resources then, and their conflicts, may inform reasoning and decisions regarding pedagogy, curriculum, instructional guidance, etc.

In this dissertation, I aim to identify some resources that seem productive in engineering design. The decision "molecules" are not necessarily coherent, stable entities of concepts, and I would imagine that teaching the same thing in two different situations creates different coherence of resources. The resources framework allows me to look for what "bubbles up" in some moments, but certainly the resources identified are not all of the resources that are either present or even in use at one time.

2.7.1 Knowledge as Fabricated Stuff, Knowledge as Transmitted Stuff

Epistemological resources are bits of reasoning "concerning the nature of knowledge, knowing and learning" (Elby & Hammer, 2010, p.3). Epistemological resources are contextually activated and may form into different epistemic frames to inform professed epistemologies or enacted epistemologies (Louca et al., 2004). Along the lines of Hammer, Elby, Hammer, Scherr and Redish (2005), the epistemological resources that I have adopted in this analysis center on the ways that knowledge is transferred, which comes into play as we discuss "instruction" from a teacher to students in the average high-school classroom. The researchers posited that transfer of knowledge may be conceptualized differently with various epistemic resources. "Knowledge as fabricated stuff" is a constructivist resource meaning that what we know comes from what we "put together" ourselves. "Knowledge as fabricated stuff" might be obvious when a teacher says, "I know about the magnetic field because I conceptualized it from all these data points." This resource might influence a teacher to instruct students to synthesize a conclusion instead of looking it up, because the teacher might think that knowledge needs to be constructed from reasoning and that students won't be learning if they just look it up.

Another epistemic resource is labeled "knowledge as transmitted stuff." Maybe the teacher thinks that physics knowledge, like that about magnetic fields, is learned from seeing a diagram of magnetic field lines, not from messing around with a magnet. Maybe the teacher thinks that really, physics knowledge is the stuff she was told, and it is the same stuff written in the physics book. Maybe she thinks that if she can just get it into the heads of her kids—maybe piece by piece, but just get it in there—then they are learning.

Both of these epistemological resources about the nature of knowledge may exist together in the individual's pool of reasoning at the same time, but this framework suggests that an individual's actions may be explained by thinking about what resources are being called upon in any given moment.

Epistemological resources are not innate abilities. Instead they inform what skills and decisions an individual employs at any given time. Resources can be "called up" or be influential in some instances, and not be called up in others. This theory helps to explain why a single human's actions may seem to reveal internally conflicting "beliefs;" perhaps resources are just surfacing differently moment-to-moment or situation-to-situation.

Try to imagine how this might look in teaching physics. Suppose that the teacher sees memorization as an activity tied to learning. She gives out a paper that lists parts of the fundamental particle model and expects that students "learn" them by remembering their symbols and listed properties. Perhaps she recalls learning the fundamental particle model similarly, repeating a mnemonic device in her head over and over until she learned the particle names. This is an example of learning by transmission—the material on the page goes into the brain. That is how this teacher thinks you should learn about these totally foreign, small, obscure pieces of matter. This teacher is calling upon a "knowledge as transmitted stuff" epistemic resource to guide her decision about how to teach the fundamental particle model.

Suppose this same teacher now wants to teach moments of inertia. She insists that all students try sitting on a spinning stool and extending and contracting their arms with weights in their hands. She thinks that experiencing the changing angular momentum will help the students internalize how mass distributed from the axis of rotation increases moment of inertia. In this different situation, the same teacher pulls up a more constructivist-oriented epistemic resource, "knowledge as fabricated stuff," constructed from experiences and reasoning.

2.8 Conclusion

This chapter reviewed literature on engineering-design recommendations and possible integration issues, and two models of engineering design for high-school science were compared. Research on high-school physics teachers attempting engineering design has not explored the epistemic dilemmas they may face when teaching a new content thread in their already packed teaching schedules or when teaching a typically divided content (engineering design and sciences) in the same science class, or how using processes of engineering design to teach content may mirror the difficulties faced when using inquiry processes to teach content.

This study addresses these omissions by asking what tensions exist in integrating engineering-design instruction reform in high-school physics and what resources, if any, assist a physics teacher in adopting engineering-design integration reform.

If authentic engineering design is enacted, we have reason to expect that epistemological misalignments might cause teachers to take up engineering-design frameworks in different ways than NGSS recommends, as evidenced by previous studies of teacher epistemologies and decision making in reform implementation. My research and analysis design expands upon the data collection and analytical processes that I think will help answer the research questions that are stated in Chapter 3.

Chapter 3: Methods

My research design is centered on the needs of the teachers and the investigation of my research questions. This chapter first reviews the needs of the teachers I worked with and my research questions. Next, it describes the research plan in detail and provides rationale for the experimental and analytical designs.

3.1 Research Questions

This study meets a demand for research on engineering design in K-12 education by investigating how a team of three high-school physics teachers integrated engineering-design instruction into their content physics classes. The study began with two overarching research questions. (1) What problems, if any, do current physics teachers experience when they try to teach engineering design in physics courses? (2) What helps physics teachers overcome the problems? As the study progressed, I also began to ask another question, (3) What are the underlying causes of these problems? This led me to my final two research questions. (4) What tensions exist in integrating engineering-design instruction reform in high-school physics? (5) And, what resources, if any, assist a physics teacher in adopting engineering-design integration reform?

Chapter 4 looks at the team of teachers as they co-planned and taught their first engineering design challenge using reform-like instruction. I identify three tensions that seemed to interfere with authentic engineering-design integration.

Science teachers, teacher educators, curriculum writers, and professional developers are my intended audience for Chapter 4, especially those involved in middle and secondary science education. Elementary education readers might need to do some extrapolation or refitting of what is appropriate for science in the lower grades. For instance, engineering design in elementary is still data-driven, but the expectation for graphical pattern emergence would likely be different.

Chapter 5 looks specifically at the reasoning of teacher Leslie as she planned and taught her first engineering design challenge alone, to identify and investigate any productive reasoning resources that assisted her in her engineering-design integration. Teacher educators, educational psychologists, and NGSS implementation researchers are my intended audience for Chapter 5. This audience also need not necessarily be physics- or secondary-education oriented. Elementary science teacher educators and elementary curriculum developers may also find the notion of productive resources useful for thinking about engineering-design integration.

3.2 General Study Design

Overall, this study was a qualitative, exploratory analysis of how teachers integrate engineering design into high-school physics instruction. I used an ethnographic participant observation (PO) method (Spradley, 1980) for the study. This enabled me to be embedded as a researcher while participating as a moderately active team member in the research setting. I was an instructional coach of sorts with the team, not an employee, but the teachers invited and welcomed me to share my knowledge of engineering-design instruction with them. I observed, reflected, sometimes taught, and frequently planned with the teachers, but I always remained a consistent participant in the local engineering-design planning and implementation. My experiences, observations, and analyses were informed by the experiences my subjects and I shared (Baxter & Jack, 2008) including class periods, planning sessions, lunches, planning from home, and happy hours.

3.2.1 Research Setting

The research setting was an urban-suburban high school near a Mid-Atlantic city, which I call “Merlin High School.” Merlin boasted over 2000 students speaking over 90 languages at home. The demographic profile was 39% white, 34% Hispanic/Latinx, 10% African American, 10% Asian, and 6% multiple races, with 39% of all students considered economically disadvantaged (i.e., qualifying for free and reduced lunch.) The four-story building was relatively new, finished in 2007 with high environmental honors, and was completely decked out in the school colors from the stair risers to the LED lighting in the main hall to the lockers and trim.

I taught physics at Merlin from 2007 to 2012 and remained friends with the teachers there after I left. Three of the four physics teachers there in 2015 heard about my research interests, including engineering-education research, through social avenues; and in May of 2015, the three subject participants casually asked me to talk to them about engineering instruction in physics. I then asked if we could do that intervention as part of a research study over the next school year, and they agreed.

I contacted their principal and the superintendent's office, and over the summer I wrote IRB proposals, district proposals, and a grant proposal to fund materials, food for planning sessions, and a small stipend for the teachers. By the end of August, the approvals were in place, the grant was approved, and the teachers consented to participate.

Although this was not a study of the students, collecting data in the classrooms required student assent and parent consent. I explained in class and in a letter sent to homes that the study was not about the students, but I requested that they consent to being video and audio recorded collaterally as I studied the teachers. The students and their parents were offered the opportunity to opt out of being recorded and to opt out of having recordings of them be shared. By this process, I received consent from 175 of the students in eight classes during the 2015-2016 school year. The teachers never knew which students opted out, but the teachers provided me with seating charts so I could try to make sure opt-out students were not in my camera frame. In sharing ongoing analysis, I selectively shared data to minimize exposure of opt-out students.

3.2.2 Subject Teachers

My subject teachers were the ones that had approached me with interest in engineering design and in co-planning engineering-design instruction for their classes. “Katniss,” “Leslie Knope,” and “Anna” (who picked or okayed their pseudonyms) are all in the majority demographic of teachers in the United States:

white women. However they are in the minority in physics; only one-third of high-school physics teachers are women (Banilower, 2013). In 2015-2016, Merlin’s physics department was a statistical anomaly because three-quarters of the physics teachers were these three women. The fourth teacher, “Eagle,” did not teach any of the same on-grade-level physics classes as the other three and was not interested in incorporating engineering design into his classes. He joined the study out of curiosity for one planning session in late October, but he was never observed or interviewed and was excluded from the dataset.

The three women had been planning their “on-grade-level” (mathematics co-requisite of algebra one) physics curriculum together for two years before the fall of 2015. Their collaboration was robust and centered on mutual responsibility, joint leadership, respect, and trust. (Evidence for these comments is provided in Chapter 4, but because of my previous informal experiences with the teachers, I was aware of their norms of communication and collaboration before the study began.) They shared lots of materials and habits including communication norms like goal setting, reflecting, delegating, and asynchronous workflow; management of curriculum through planning sessions, equipment, and ideas; professional requirements like SMART goals and field trip proposals; classroom materials like presentations, handouts, labs, assessments, and grade remediation; and access via online Dropbox and Google Drive folders. They were also social; they ate lunch together almost every day and ventured to social happy hours with the rest of the science staff. No one was the boss in this team, and everyone’s individual strengths, weaknesses, needs, obsessions, and compulsions were fodder for a smile and a hug, not a tease or a reproach. If someone was absent, the rest of the team helped to get the substitute teacher on track. If someone was busy, the rest picked up the slack without complaining. If someone was concerned about a lesson, they were invited to watch the other teachers do it. This was truly a thoughtful, supportive, professional, collaborative team.

Katniss was the youngest of the three teachers and in her third year of teaching. She had graduated from a large Midwest university with a degree in physics and finished her masters in physics teaching in 2013. She was active not only in the physics teacher group at Merlin, but also in an International Baccalaureate (IB) physics-planning group with teachers from multiple districts, and had a national teaching fellowship. In her spare time, she also practiced, coached, and organized parkour meet-ups for women and girls, which influenced what she valued as a teacher. In my initial interview with her, Katniss highlighted her goal of helping students become risk takers. She picked her own pseudonym, a reference to the daring heroine of the movie *The Hunger Games*, and the name reflects her bold, strong, risk-taking attitude.

Leslie had taught physics for six years before my study began, three of them at Merlin. In 2015-2016, she was teaching three sections of on-grade-level physics and two sections of second-year IB physics. She had received her undergraduate degree in physics and her masters in teaching secondary science. Teaching was her first career, and she had previously taught other sciences in addition to physics. Leslie is a jubilant person and teacher, constantly silly and spunky, in touch with pop culture references and student interests. One of Leslie's instructional goals was to be quiet and let students surprise her. When students found a new interesting connection, or even when they were cutting her safety gloves in half by mistake to get the lining, she thought it was good fun. In our first interview, she talked about wanting students to be "innovative without limits." Leslie named herself Leslie Knope after Amy Poehler's character in the comedy television show *Parks and Recreation*, and the name reflects her quirky, trusting, and serious sides.

Anna was the oldest of the three teachers. She had taught for over twenty years in diverse settings and areas of science including astronomy, biology and physics, but her degree was in biology, the subject she describes as most within her "wheelhouse." Anna was an active mother of two teenage boys; when they had swim practice, she went swimming. She took walks during lunch to keep her mind and body centered during the busy school day. She made a conscientious effort to get to know each of her students, and she used that knowledge to make solid student partnerships in class that lasted the entire year. Near the beginning of the year, Anna said, "I'm not trying to be tricky," exemplifying the straightforward approach she took to teaching. She was direct, honest, and very respectful of her students. After a year of equivocating over a pseudonym, I finally picked "Anna" because of the song that the character Anna sings in the King and I, "Getting to know you getting to know all about you… ." Teacher Anna got to know her students so well that by the end of the year they were in tears to leave her class, and she was in tears to lose them to graduation.

These three teachers opened their classes, their closets, their lunch breaks, and their planning meetings to me. They set aside the fear of critique that causes some teachers to close their doors when class starts, and instead mostly welcomed observation, suggestions, and new perspectives. They took on more hours of planning, re-writing labs, and re-sequencing units to include reform-oriented engineering design while remaining true to their individual and collective interests and priorities.

3.3 Data Collection Methods

For this study, I observed these three teachers' eight sections of 11th and 12th-grade physics (about 200 students total) at Merlin, beginning on the second day of school. Because they were a pre-existing team that co-planned eight sections of the same level physics class, I began with descriptive observations of the team as a whole, observing 29 classes in the first two months of school, September and October 2015. They were each compensated $200 per semester and received a copy of the NGSS and Appendices, and I bought them lunch or snacks once a month with funding from a research grant. In January 2016, I became a substitute in Merlin's county and subbed for all three teachers during the spring semester for a total of 10 days.

My observations eventually became more focused, based on the lessons that the teachers were planning, and finally became very selective, based on specific lessons and class sections. Most of this narrowing came organically from the PO methodology; as I became more familiar with the subject teachers and what they would teach as related to engineering, I felt a pull towards investigating certain compelling stories more deeply. When patterns seemed to emerge, I sought out other situations where I believed I might see a confirmation of that pattern, or I looked for lessons where I thought the pattern might be missing to confirm some causes of the behavior. But some of the narrowing came from preferences of the teachers; for example, teacher Anna decided in November that she preferred that I observe only on her third time through a lesson, limiting my opportunities to observe her.

During classroom observations, I ran an audio recorder near the teacher at the front of the room, and video recorded from the side or back of the room, depending on where consented students were sitting. I usually sat in the back of the classrooms and took field notes, refining my note-taking template four times throughout the year (the final observation template is attached as Appendix 3.1). During classes, I typed field notes using four columns: one each for a time stamp from my audio recorder, and the actual time in the room, another documenting the activities in class including quotes I heard and observations of the teacher, and the last one analytical including my interpretation and reaction to the observations. I tried to summarize every class in a table at the top of each field-note document, including the main content in the class, the instructional modes used in the class, and any other interesting observations. I kept a data log where I catalogued the type of data in the data set piece by piece, keeping track of seemingly significant moments and insights from the data, and noting the digital storage location for each field note, audio recording, and video recording.

In early analysis, I realized that audio recordings were very valuable, sometimes more than video, because the quality of the audio was much better for my purposes and the battery never gave out. I also felt like the audio recorder was less obtrusive for the teachers and students, so I tried to collect as much audio as possible, sometimes in lieu of video or even note-taking. For instance, when observing teachers interacting with student groups, bringing in a video camera or plopping down at the lab table with my laptop often would have been too intrusive, so sometimes I simply carried the small audio recorder in my hand and walked toward the table. From three to eight feet away, I could capture a clear audio recording and then return to my laptop to comment on the observation minutes later. Sometimes, I asked the teacher to hold the recorder in her hand as she walked from group to group. By noting the teacher's location relative to the time in my field notes, I could later listen to the audio and, by using the timestamp, my notes, and context clues, pick out moments of conversation with certain student groups.

In addition to classroom observations, I frequently met with the teachers for formal planning sessions and informal discussions at lunch, after school, or just in the hallways. Only for the first planning session did I set an agenda and feel like a professional developer of some kind, the kind they had asked to come "speak to them." (See Appendix 3.2 for a brief description of the intervention methods.) After the first one, all further planning sessions were highly collaborative, with the teachers and I all equally contributing ideas for instruction in physics or in engineering embedded in the physics classes.

Four formal interviews were conducted with each teacher during the year, one per quarter, and a last member check (a discussion with the participant for descriptive and interpretive validity) was conducted in November 2016. The interviews were semi-structured. They began with a set of interview questions, but they remained loose in their protocols in order to ensure that the natural flow of conversation could be respected and followed. In total, I collected about 150 hours of observations, about 50 hours of planning sessions, and about 12 hours of interviews. Other informal communications, such as text messages and emails, also became part of my data set as the study progressed.

3.4 Analytical Methods

I used memoing, both audio and written, to help me summarize my thoughts. At times, it felt like just as soon as I turned a recorder off I would see or experience a significant moment or realization. Memoing helped me to keep track of these thoughts outside of observation. I also kept a running list of themes I noticed and discussed these themes with my colleagues at my university, transcribing data as necessary and tagging important moments in field notes, on my data collection chart, and in the qualitative-analysis software MAXQDA11. I wasn't coding at the early stages; I was tagging to prevent snippets of conversation or instruction from slipping into remote recesses of my data set. I amended my IRB in May to allow the use of transcription services, and asked the teachers to sign a new consent form to allow transcription.

All three teachers were usually very calm and in control, so I found myself drawn to think about the moments when the teachers showed significant frustration in class. Observing their engineering-design instruction, I started to pay close attention to where they seemed most out of sorts during the lessons. It seemed natural to me that frustration might cause these teachers to stop using engineering design, and indeed, in a previous pilot study, I'd seen that frustration cause another teacher to stop using engineering design in the middle of a lesson.

To understand what frustrated them, and how they got through it if they did, I compared the teachers' non-engineering-design instructional patterns and habits to their engineering-design instruction. This helped me identify moments where the engineering-design planning and instruction seemed a lot like their regular physics practice, places where engineering design seemed not to fit with their regular physics instruction, and places where their regular habits and routines seemed to support engineering design.

It seemed unavoidable to compare the teachers to each other though that was specifically not a goal of this research. I was afraid that if I compared them at all, then one would appear to be better than others, and I wanted to avoid that. I assume that all teachers are doing what they think is best, even though their instruction might manifest differently. To counter natural tendencies to compare, I sought a productive-resources framework instead of a deficit framework. This led me to note and discuss the positive aspects of actions with my research peers and the study's teachers.

To process my ideas and observations, I engaged in analytic memoing, presented ongoing analysis and findings at the engineering-education research group, consulted with my research peers (on the IRB), and storyboarded ideas while thinking and writing. I began to feel that certain moments in the timeline of the story were most significant for demonstrating frustrations and successes, and those moments, as well as all the interviews, were transcribed completely either by me in Inqscribe, or by the service Rev.com. Then I reviewed them for accuracy. Some observations had multiple recordings of the same moment, so all of those were transcribed to capture a full picture of the teachers' interactions.

Many themes emerged from the data, but I narrowed these to two ideas for published papers that I felt would provide readers with a sense of these teachers' difficulties as they brought engineering design into their practices. The first paper, which is embedded here as Chapter 4, is a description of three issues that arose as all three teachers planned and taught the Parachute Challenge. The second, Chapter 5, describes my conclusion that inquiry facilitation skills and relevant epistemic resources assisted Leslie in teaching the catapult challenge and helped her decide to persist with including a substantive design component, despite her initially feeling that the design activity was overly chaotic and perhaps unproductive. Specific analytic methods are included in their respective chapters.

During the writing process, I returned often to my field notes, class transcripts and observation videos to stay close to the data, corresponded with my advisor and research team at my university, and sought out additional scholarly research to assist and push my thinking. As my conclusions became clearer I met with my subject teachers individually and described the conclusions I was writing, and later conducted an extended member check for interpretive validity with each teacher and shared with them the draft chapters they wanted to read. Each teacher approved my conclusions and found them informative.

3.5 Study Limitations

This study is limited in its generalizability because it uses a qualitative methodology involving a small, purposefully selected sample of physics teachers. However, the study methodology of sustained classroom observations, interviews, and researcher-involved teacher planning sessions helped create rich, vivid depictions of how these teachers teach and think. These descriptions may contribute to an understanding of the underlying mechanisms by which teachers' beliefs, habits, and goals affect their use of engineering design in instruction. I aimed to demonstrate a "paradigm case of more encompassing phenomenon" (Cobb, 2000. p. 325), that of including engineering in mainstream science instruction.

3.5.1 Were These Very Special Teachers?

My sample included three teachers who were highly self-motivated to include engineering instruction in physics classrooms; other schools and other teachers might not have or act on similar levels of motivation. These three teachers do not work in an NGSS state, and their county and state do not require them to use engineering in physics, unlike the 41 states that have engineering standards in science (Kersten, 2013). Hence, this sample may not reflect all U.S. physics teachers' motivation towards engineering instruction. However, this sample is useful in the sense that it illustrates a best-case scenario of teacher motivations for science reform; I know that they were highly motivated to do engineering in their classes.

The state in which they work also does not have an end-of-course examination for "regular" (on grade level) physics, so these teachers were not burdened by needing to teach to some physics test as many teachers are in the U.S. Although these three are beholden to state and county content standards, they had fewer time demands and fewer curriculum structures placed on them because they did not have an end-of-course test to prepare for. So, they were freer than other teachers to try engineering, even if it took up time.

3.5.2 Addressing My Subjectivity

My conceptualization of engineering design, and my interpretation of what quality engineering-design instruction is, limits the study. To address this limitation, I try to be explicit about the materials and instruction used during the study and to include sufficient data to enable readers to reach their own interpretations or at least be able to critique my interpretations. A discussion of my conceptions of engineering design processes and features and their comparison to NGSS is included in Chapter 2.

3.5.3 Keeping My Familiarity In Mind

I feel privileged and grateful to have had access to my teachers' classrooms, their conversations, and even their private moments. I realize that I risk making false assumptions when I feel too comfortable in a research setting, but it was natural for me to feel comfortable there. I previously taught at Merlin for five years, ending four years before the study. I have strong ties to the school and its teachers, having grown up near Merlin and having built a life of relationships with many Merlin teachers from childhood soccer teams, high-school band, and local social connections.

Also, my participants and I are friends through teaching together. I was consulted when Merlin hired Leslie, and I worked with her at Merlin for two years; I was consulted when Merlin hired Katniss, whom I already knew separately through a teaching fellowship; and Anna and I crossed paths before this study, when she worked at another local school before Merlin. When working at Merlin and in the years since I left, I have joined these and other Merlin teachers at happy hours, house parties, craft parties, and baby showers.

I was very comfortable in the research setting, so much so that I had to be careful not to overstep my place. I had taught in two of my subject teacher's classrooms and continued to feel some affiliation to the rooms even as a visitor. From helping to reorganize the stock rooms to making coffee and fixing the copiers, everything felt natural and familiar. My old coat hangers were still in use, my coffee mug was still on the pegboard, and the classroom calculators still bore my name. Getting wrapped up in the frenzy of the beginning of the school year, I had to consciously remind myself not to breeze around so casually. The stock room was now someone else's office, and that teacher needed privacy and space, just like I needed when I was teaching there. So it took us all a few weeks to adapt, and then it was fine.

Being back at Merlin was a joy, and I was very happy to go there on observation days. More often than not, I could hardly contain my excitement and would get there as early as the teachers to help set up equipment. I pitched in to help make iPhone mock-ups for the iPhone engineering design challenge, created drop plates to work with the force probes, helped to revise documents from home, and did other semi-teacherly things.

Analyzing the collected data and writing this dissertation was also a joy, like being back in conversation with those teachers. But again, my extreme familiarity can be a problem and must be held in check. It is likely and probable that my familiarity with Merlin influenced my interactions with the subject teachers, my data set, and my analysis. Likewise, my observations were likely influenced by my prior experiences observing student teachers for two years. No doubt my observations, initial coding, and analyses are based on various teaching moments to which I responded as a student-teacher supervisor in prior years.

On one hand, my familiarity enabled me to cut through formalities and likely garnered me trust; but on the other hand, there are many examples where my knowledge in some situation (for example how the roller coaster project was developed) precluded me having to ask about it. Sometimes I realized and remembered to ask about familiar items to get into the teachers' perspectives and away from my own, but sometimes I forgot to. I am lucky to have been pushed by my committee and academic peers to justify my claims with data, not memories or assumptions, although the ethnographic nature of this study does allow for some of these memories to act as data.

3.6 Positionality Statement

My perspective as a researcher is surely influenced by my identity. I am a 35-year-old white woman; my parents both had graduate educations—one MBA, one MBA and PhD—and raised me in an affluent suburb of a large city. My education was privileged and included early reading, great public schools, gifted programs, summer enrichment, and music lessons. I graduated in physics and sculpture from a prestigious university and went on to an elite art fellowship before going to graduate school for my master's in science education. I taught physics for five years at Merlin High School before I returned to graduate school. Two parts of this story especially need more discussion: my background in physics and art, and my experience teaching at Merlin.

I view art and science as closely related and informative of one another, so I try to use art to both learn and teach physics principles and phenomena. The sculptures I make are usually large mechanical installations, and my process is very physical. I craft with wood, metal, water, and light. Some of my aesthetic and physical proclivities are so embedded that it is hard to remember that they exist. For instance, I have an aesthetic preference for simplicity and order, which, in my engineering-design instruction pilot study, resulted in a preference for simple designs. This must also influence my values outside of art, including in instructional planning, instructional actions, and classroom assessment. Additionally, I naturally assume that problem-solving is engaging, and that engagement leads to more interest, increased buy-in, higher achievement, and better outcomes; but luckily, I'm not alone in that assumption (Delpit, 2012; NGSS Lead States, 2013d; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001).

I also think that making things can be a form of learning in science. I found over and over that I needed physics, including actual numbers, diagrams, and equations, to solve art construction problems, and I had to learn such things to finish my designs. I expect this assumption, that one can learn content physics from making objects, to be a fundamental sticking point in teachers' adoption of engineering design in physics because over and over again I have had to explain that making is learning for me in my artistic practice.

However, I am not an engineer; I identify as a physics teacher. So, in this study, I tried to position myself as a teacher-collaborator, rather than as an engineering expert. But even then, I came back to Merlin with some authority as a PhD student, a member of the KSTF Lever Engineering Group (a group of science and mathematics teachers interested in how to effectively and appropriately incorporate engineering design into content mathematics and science classes), and a member of the University of Maryland Engineering Education Research Group (EERG). I also had clout as a former physics teacher at Merlin and from other achievements, including visiting the South Pole as a teacher liaison to the IceCube Neutrino Observatory and being a top-50 finalist for NASA astronaut selection in 2013.

In this study, that authority and clout did affect the subject teachers' perceptions of me. All three variously said they were nervous to have me in their rooms when the study started. Leslie said that she thought I was an authority on engineering integration, and she was concerned about getting the engineering design "right" and did not want me to judge her for getting it wrong. I worked hard to not be domineering in planning and conversation, and to discuss and validate all of the teacher ideas, adding in many of my own, to show that many ways of thinking were appropriate, not just one.

With time came routines and normalcy, and things got more comfortable in all three teachers' classes. After they had taught a few engineering design challenges, I noticed they all were more comfortable with engineering design. I knew we had turned the corner on them feeling authoritative about engineering design when they each, independently, talked with me about how to share what they had learned about engineering-design integration. Anna wanted to speak at a county-wide science teacher meeting, Katniss wanted to share engineering design ideas with her IB planning group, and Leslie wanted to work with other local and national teacher groups involved in engineering-design integration. However, Anna never fully got over her general sensitivity to my presence; for the entire year beginning in late September, she preferred that I come on her final run through a lesson to ensure she was feeling confident before I observed. This sensitivity, I think, was less about getting the engineering "right" and more about feeling uncomfortable overall with someone watching.

3.7 Timeline of the Study

This timeline shown in Figure 3.1 is intended to orient the reader to the chronology of the study and the school year. It includes the teachers' physics content sequence and their engineering design challenges, as well as the study's data collection statistics. Extended discussion of the timeline is provided in the Appendices. Appendix 3.3 is a table of the year's events by month, Appendix 3.4 is a table of the observation minutes by month, and Appendix 3.5 is a longer narrative of the entire year's timeline.

Physics Instruction	Nature of Science/ Patterns	Kinematics	Forces & Newton's Laws	Impulse & Momentum	Energy, work and power	Electricity & Circuits	Waves, light & sound
Approx. weeks	4	7.5	7.5	4	7	4	6
Engineering -Design Instruction			1) Pumpkin Chunkin' Challenge 2) Parachute Challenge	iPhone Drop Challenge	Roller Coaster project		Music Instrument Challenge
Observation	9 cls 0 pln	20 cls 5 pln	29 classes 9 planning	9 classes 3 planning	16 cls 1 pln	4 cls 1 pln	31 classes 3 planning

Figure 3.1 Instruction and Observations Timeline

3.7.1 Timeline in Brief

In September 2015, I introduced myself and the study to the students in all eight sections of on-grade-level physics at Merlin and began to make class observations after the vast majority of student consent and parent assent forms were collected. In September, I observed nine block classes (90 minutes each) as the teachers worked through a Nature of Science and Patterns Identification unit. I also conducted the first round of teacher interviews.

In October, in our first professional development session, the teachers co-constructed an understanding of the engineering design process by doing an engineering design challenge, modeling the process, and comparing that process to other models of the engineering design process. Their interest and motivation came alive with the idea of contextual problems, and we discussed how we could use our future meetings to tailor their existing units to include engineering design. The teachers expressed two big concerns in this meeting: content coverage and a fear of widely diverging student ideas.

In October and November, the teachers taught kinematics. I observed 31 block classes, and we had nine planning sessions. My observation routine smoothed out as I negotiated being both a passive classroom observer and active collaborator with the teachers. In November, at the end of the kinematics unit, Leslie planned her first engineering design challenge, the Pumpkin Chunkin' Challenge, and she and Anna both taught it. Anna struggled to find her groove in the lesson and called it off for one of her three classes. Leslie moved from feeling unsure about what was acceptable in engineering design to feeling more comfortable and having fun.

In December, the teachers all co-planned and taught an engineering design challenge built upon their previous terminal velocity lab, to support their instruction on forces and Newton's Laws. I observed 11 classes, we had four planning sessions, and, I completed the second round of interviews. I had a breakthrough realization about the relationship between teaching inquiry and engineering design for Katniss and Leslie as nascent cohesive patterns of behavior formed between physics instruction and engineering instruction.

In January, February, and March, the teachers planned and executed an iPhone Drop Challenge with two rounds of optimization, based on their previous project. I observed 24 block classes and participated in four planning sessions while the teachers worked through unbalanced forces, energy, momentum, and impulse. I conducted the third set of interviews following the iPhone challenge.

In April, the teachers did a roller coaster project they had done in past years to teach and practice energy, work, and power. I observed eight classes and participated in one planning session. Leslie drew distinctions between engineering challenges and physics projects, and she became interested in teaching other teachers about engineering design.

In May and June, the teachers taught waves and sound. They planned and taught elements of engineering design in their existing musical instrument design challenge. I observed 31 classes and three planning sessions, and conducted the final set of interviews. Leslie continued to explore ways to spread her interest in teaching teachers, Katniss reflected on content-inclusive engineering design, and all three reflected on the value of engineering design for disinterested students.

3.8 Summary

This study was conceived to learn about engineering-design integration in physics and took advantage of a chance opportunity to work with three motivated, already collaborative teachers in a familiar high-school physics department. I was fortunate to have the opportunity to study these teachers, and now it is my honor to share with you their teaching and my analyses as I investigate what tensions exist in integrating engineering-design-instruction reform in high-school physics, and what resources if any assist a physics teacher in adopting that reform.

Chapter 4: Tensions With Engineering-Design Integration in a Co-Planned High-School Physics Terminal Velocity Lesson

ABSTRACT

Integrating engineering design into K-12 science will be a new effort for many U.S. teachers. It should be of great concern then that only 4% of elementary teachers and only 7% of high-school science teachers report feeling “very well prepared” to teach engineering (Banilower et al., 2013). Even so, all K-12 science teachers are now expected to integrate engineering design into their science instruction (NGSS Lead States, 2013d). Little is known about how science teachers will teach engineering concepts, but some studies have begun to report how high-school physics teacher take on the task (Dare et al., 2014). This paper explores the tensions a team of high-school physics teachers encountered as they co-planned and taught an engineering design challenge focused on terminal velocity.

This paper is a chapter of a qualitative, participant-observation dissertation study on engineering integration in three teachers’ high-school physics instruction over the course of one school year. The physics lesson in this paper was selected for analysis because it was the first time all three teachers planned and taught the same engineering design lesson.

Three tensions emerged in the teachers’ instruction: (1) between truly integrated engineering-design instruction and more traditional physics content; (2) between the time needed to do adequate data collection and the shorter time constraints imposed by fitting the lab into one class session; and (3) between supportive classroom routines and routines to facilitate divergent student thinking. These tensions arose when the teachers used regular instructional methods that may have undermined the exploratory (derivative) learning and designing processes in engineering design challenges. These tensions came from a lack of clarity within this teacher group of what engineering design is and how it relates to scientific inquiry, and from the teachers’ genuine and natural desires to simplify and expedite content acquisition for their students.

Understanding these tensions can help teacher educators, practicing teachers, and student teachers better prepare for engineering-design integration. Practicing and student teachers may reflect on why and how pedagogical moves that are productive and natural in other types of instruction might be at odds with engineering design as envisioned in the NGSS. Learning about these tensions could help teachers work towards a deeper understanding of engineering design and the nature of engineering, and how it is similar to and different from the nature of science. This study suggests that the integration of engineering design into content science instruction might require substantial preparation and engagement around these tensions.

4.1 Introduction

In December 2015, a high-school physics planning team—Anna (pseudonyms are used throughout), Katniss, Leslie, and I—co-planned a Parachute Challenge to teach terminal velocity concepts. The teachers were participating in my one-year study to learn about engineering design and practice enacting engineering-design integration. My observations of their planning and instruction identified issues in engineering-design integration and revealed how the teachers handled these issues.

This chapter tries to describe, and begins to explain why, teachers made the decisions that I observed in their planning, instruction, and reflection surrounding a terminal velocity lesson involving engineering design. In this study, I asked what tensions exist in integrating engineering-design instruction in high-school physics. Each teacher's actions and words enabled me to identify various tensions between NGSS-oriented engineering-design instruction and other reasonable goals and assumptions found in their science teaching.

This chapter focuses on three tensions that the teachers faced individually and as a group: (1) The full integration of engineering and physics was in tension with the more traditional separation of physics content learning from the engineering design process. (2) Needing to complete the lab in one class period was in tension with collecting adequate data to drive design decisions. (3) The teachers' supportive classroom routines were in tension with students' divergent design thinking and agency. Each of these tensions reveals underlying assumptions and beliefs that the teachers had about teaching physics and engineering design. These tensions and the ways that these teachers worked through them may be instructive for understanding how other teachers might take up the NGSS engineering design integration reform.

For curriculum developers, science teachers, teacher educators, and professional development (PD) providers, it is important to recognize the problems teachers face when planning and teaching reform-minded curriculum. What different teachers do during engineering-integration instruction can help us understand how otherwise productive teaching methods may differ from their intended use when placed in engineering-design contexts.

This study does not judge or evaluate decisions made by the teachers, but rather tries to understand what their conscious and hidden motivations were. If the goal of reforms such as the NGSS is to have teachers use engineering design in science classrooms, then reformers and researchers must acknowledge and investigate the complex interactions between (1) teachers' understanding of engineering design and engineering-design instruction; (2) their fears, goals, and assumptions about teaching engineering design; and (3) their goals and requirements for doing engineering design to teach science within their content classes. This study begins that investigation.

This chapter first reviews relevant literature on engineering design and the NGSS, and explores frameworks for, and visions of, integrated engineering-design instruction. It then describes the three teacher's motivations for turning a physics lab on terminal velocity into an engineering design challenge and how they planned challenge, including their concerns about engineering-design integration prior to instruction. Next, the chapter looks into each teacher's classroom during the two weeks that the challenge was conducted to see how their plans and concerns played out, describing how the teachers dealt with their concerns during the instruction. Finally, this chapter draws conclusions regarding how the three tensions affected instruction, discusses what these findings imply for engineering-integration reform, and suggests further research in this area.

4.2 Literature Review and Conceptual Framework

Literature pertinent to this chapter includes descriptions of engineering design and how the hallmarks of engineering design are translated into my conceptual framework for engineering design in high-school science instruction, with attention to describing elements of engineering design that were found to be problematic or minimized in my observations.

4.2.1 Engineering Design in K-12 Science Standards

The term "engineering design process" refers to a set of skills, actions, and mindsets that engineers use to solve specific problems for specific purposes. Evans, McNeil and Beakley (1990) described engineering design as "a systematic, intelligent process in which designers generate, evaluate and specify concepts for devices, systems, or processes [to] achieve clients' objectives [while] satisfying a specified set of constraints." Engineering design has specific attributes, such as analysis, constraints, modeling, optimization, and systems within a highly iterative process (Katehi et al., 2009), and requires certain engineering mindsets, including, for example, the embrace of multiple possible solutions (Katehi et al., 2009), the utility of productive failure (Petroski, 1992), alternating and iterating through divergent and convergent thinking (Radaideh et al., 2013), and careful monitoring of progress towards goals and subgoals.

Traditionally, engineering students in higher education learn engineering design separately from the engineering sciences (e.g. fluid dynamics, electrostatics, physics, biochemistry, electrostatics, etc.) that comprise the bulk of engineering coursework (ABET, 2013; Grinter, 1955). This bifurcation has been blamed for engineering students and graduates not understanding how content mathematics and science courses are connected to engineering practice and careers (Froyd & Ohland, 2005). Some popular K-12 engineering curricula (Project Lead the Way or PLTW, for example) follow that tradition of bifurcation. But the NGSS (NGSS Lead States, 2013) emphasized how engineering design practices and science content could be learned simultaneously. "An understanding of engineering [design] practices can develop as they are used in the classroom to help students acquire and apply science knowledge" (National Research Council (U.S.), 2012, p. 201). This was a major shift away from the traditional separation, and it requires K-12 teachers to juggle the goal of teaching design processes and science content concurrently.

4.2.2 Conceptual Framework: Engineering Design in Physics

The conceptual framework that is proposed in this dissertation for doing of engineering design for high-school physics is drawn from the NGSS framework. The

NGSS describes the knowledge and skills that students should use when they do engineering design in high school as a set of practices that can be "used iteratively and in combination" (National Research Council (U.S.), 2012, p. 49) within the scope of the three engineering components shown in Figure 4.1: define, develop solutions, and optimize.

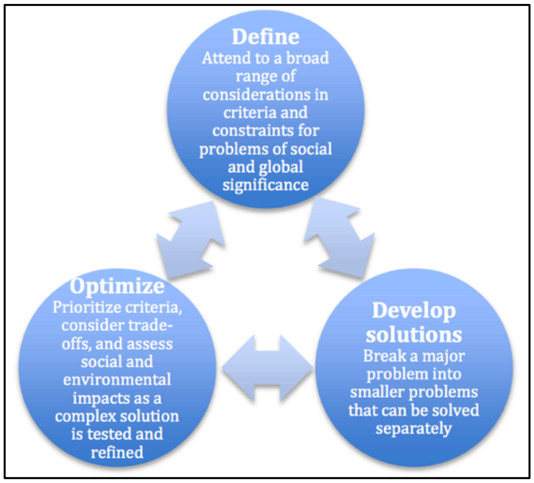

Figure 4.1 The NGSS Engineering Design Model (NGSS Lead States, 2013, p. 106)

This model shown in Figure 4.1 is an extreme simplification of the engineering design process and is intended to be used in conjunction with the eight practices for science and engineering (NGSS Lead States, 2013, p. 106), but both the model and the list of practices lack some important nuances of the engineering design process, such as creative, divergent thinking and systematic narrowing of ideas based on data (Dym et al., 2005; Grinter, 1955; Petroski, 1992).

Instead, this dissertation applies the model of engineering design that is shown in Figure 4.2.. This model was developed by a group of high-school mathematics and science teachers from the Knowles Science Teaching Foundation (KSTF). This KSTF model conceptualizes engineering-design instruction as an iterative system of four intersecting and overlapping "phases": problem definition, design exploration, design optimization, and design communication. This model also aligns with Radaideh et al.'s (2013) four-stage model for engineering design, which includes problem definition or framing, conceptual design, preliminary and detailed design and build, and design communication stages.

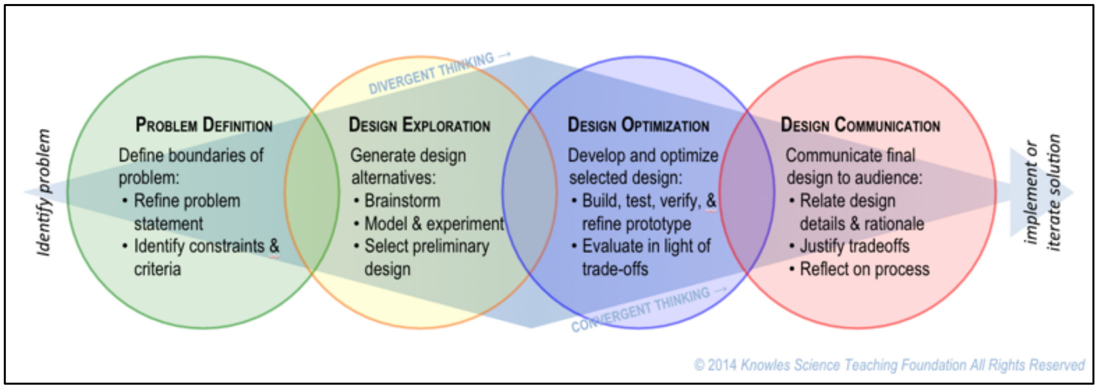

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Figure 4.2 [Also Figure 2.4] The KSTF Four-Phase Engineering Design Process Model (Johnson et al., 2015, p. 19)

The four phases of the KSTF model were intended to encompass the divergent-convergent aspects of creative thinking and brainstorming and to illustrate how explicit emphasis on communication elevates the softer skills associated with sharing a designed solution (Johnson et al., 2015). The model was also intended to offer more structure and support (possible beginning and end points, and scaffoldable pieces and relationships) for teachers who use it in classrooms.

4.2.3 NGSS Vision: Learning Content While Doing Engineering

The NGSS vision for engineering design has a three-part goal: (1) to develop an understanding of engineering practices as they are used in the classroom, (2) to teach new science, and (3) to apply previously learned science (National Research Council (U.S.), 2012). Translated to high-school physics, this goal implies that teachers will be expected not just to facilitate engineering design challenges, but also to ensure students are learning and practicing physics content.

A small body of research has shown this is hard for teachers to do. Dare et al. (2014) studied three physics teachers implementing a packaged windmill challenge that they themselves had experienced and discussed in an intensive five-week professional development. The researchers found that during instruction the teachers avoided emphasizing content physics except for including several physics problems at the end of an accompanying packet of worksheets. Two of these teachers expressed during interviews that they would have liked to emphasize the physics more. Roehrig and Moore (2012) found that using engineering design as a context to teach science frequently resulted in less than satisfactory design actions (tinkering, and trial and error) to solve a challenge, or it missed opportunities to connect science content directly to the challenge. Using engineering design to teach science content means doing engineering design and content instruction together, but neither of those studies found a successful balance between design and instruction. This study took up the call for more research on K-12 engineering-design instruction and identified specific difficulties related to engineering-design integration.

4.3 Methods and Research Setting

This chapter addresses the question of what tensions exist in integrating engineering-design instruction reform into high-school physics. The intended audience includes science teachers, science teacher educators, curriculum developers, and professional developers. This audience need not be specifically physics-oriented, or even particularly high-school-oriented. Elementary-oriented readers might need to do some extrapolation or refitting of what is appropriate for science in the lower grades. For instance, engineering design in elementary education is still data-driven, but the expectation for graphical pattern emergence would likely be different.

4.3.1 General Study Design

This study used a PO methodology (Spradley, 1980). Similar to a case study and with roots in ethnography, the PO method is within the constructivist paradigm, acknowledging and appreciating that observations and analyses are subjective as human constructs, and co-constructed by the experiences the subjects and their observer share (Baxter & Jack, 2008). Also, instead of being focused on culture, which is the usual interest in ethnography, this study focuses on classroom instruction.

Because I sometimes planned, sometimes taught, and sometimes observed in the teacher's classes and daily lives, my activity as a participant was dynamic. The PO method allowed me to be embedded as a researcher while also participating as a moderately active team member in the research setting. I was an instructional coach of sorts with the team, not an employee, but was invited and welcomed to share my knowledge of engineering-design instruction in physics with the teachers. I observed, reflected, and frequently planned with the teachers. All of our planning sessions were highly collaborative, with the teachers and I equally contributing ideas for instruction in physics or in engineering embedded in the physics classes.

4.3.2 Research Setting and Subjects

The study took place at “Merlin High School,” an urban-suburban high school near a Mid-Atlantic city, with over 2,000 students speaking over 90 languages at home. Merlin is not a Common Core or NGSS school, but it is ranked high in its state and 100% of Merlin teachers are “highly qualified.”

Physics teachers Leslie, Katniss, and Anna (pseudonyms are used throughout) invited me into Merlin High to discuss engineering integration with them, and this dissertation study evolved from those discussions. Leslie and Katniss were undergraduate physics majors who also had science-teaching masters degrees, and Anna’s background was in biology. Anna had taught for over 20 years before the study began, but only two years were in physics. Katniss had taught physics for two years before this study, and Leslie had taught for six years, some in physics and some in other sciences. (See section 3.2.2 for more detailed information about these teachers.)

The three women had been collaboratively planning their physics curriculum for two years before the study began. They also shared a strong mutual trust and respect. They shared communication norms that helped them efficiently decide on goals, divide up work that needed to be done, and complete tasks asynchronously for the benefit of the group. They assisted each other daily and even assisted each others' students as needed. They were a tight-knit, supportive collaborative team.

4.3.4 Data Collection

I began my study of these teachers' eight on-grade-level physics classes in September 2015 by making general observations using an observation technique similar to one I had used while observing student teachers. I watched how the class unfolded, made descriptive observations at regular intervals, and recorded my reactions to the observations. Over time I began to notice patterns that comprised each teachers' professional habits and practices. An initial interview with each teacher enabled me to discuss their teaching philosophies and feelings about engineering design.

In early October, I introduced the teachers to engineering design through a tower-building challenge, and they began to brainstorm how they could use engineering design to teach content physics. During the remainder of the school year, we co-planned four engineering challenges used to teach physics within the context of engineering design. The teachers were each compensated $200 per semester and received a copy of the NGSS, and I bought them lunch or snacks once a month funded by a research grant.

During engineering-design lessons and regular physics classes, I collected qualitative observation data: audio, video, field notes, and memos. I also participated in planning sessions, lunches, planning at home, texts, emails, online hangouts, happy hours, and four interviews with each teacher. Over time, my observations became more focused, based on the content of lessons and on the preferences of the teachers.

I relied on memoing, both audio and written, to keep track of my thoughts and evolving theories about the teachers' actions. After drafting this chapter, I conducted two final member checks with each teacher, one in the final interview and one in November of the following school year. In total, I collected about 150 hours of observations, 50 hours of planning sessions, and 12 hours of interviews.

This chapter is focused on the data collected during the Parachute Challenge in three planning sessions, seven classes (three Katniss, three Leslie, and one Anna), and two teacher reflection sessions, but the analysis is informed by my understandings developed throughout the year of observations as explained in my analytical methods.

4.4 Analytical Methods

This chapter evolved after observing and talking to the teachers for the entire school year. Watching the teachers' classes for nine months, I saw differences between the individual teachers' physics instruction and engineering-design instruction, but it took time to understand those differences. By labeling these differences "tensions," I was able to frame moments of uncertainty or inconsistency as a struggle between regular instruction and engineering design instruction. Eventually, after watching classes, talking to the teachers and directly interviewing them, I felt that I had identified several tensions that remained relatively consistent over time, though they did evolve somewhat over the course of the school year. I member-checked my inferences and continued to document and describe the various tensions clearly.

The tensions I noticed were more than just topics of conversation, they were persistent problems that teachers had to struggle through, and each of them seemed to be at once intuitive and counter-intuitive. The teachers agreed. Tensions were present in moments when the teachers themselves felt they were doing their job both well and poorly at the same time, and were also present in moments when they felt uncomfortable in a usually comfortable routine. To the teachers these tensions were an explanation for why some things felt deeply unsettling, and recognizing these tensions provided a way to reason through their feelings of failure.

I identified their first planning and instruction attempt, the Parachute Challenge, as the strongest example of the teachers' tensions perhaps because it was the first attempt for the teachers to plan and implement engineering design together. This lesson was also incredibly powerful for the teachers, particularly Anna and Katniss, and they remembered their team's conflicts in planning and their eventual resolutions over the remainder of the school year, even in June. Hence, the differences highlighted here are not just isolated observations; they are a reassessment and restatement of the teachers' various tensions as informed by my individual observations, comparisons across the cases, the teachers' own reflections, and coherence over time.

In this chapter, I've employed ethnographic methods in my immersed participant observation to describe, understand, and explain my subjects' actions as they each taught a seemingly identical lesson. In phase one of my analysis, I sought domains of interest (Spradley, 1980) in the engineering instruction such as "context is engaging!" and "productive struggle allowed." At first, I looked at the individuals as one grain size of analysis, and across the team as a whole as another grain size, which helped to highlight some differences between individuals. Ultimately, however, I focused on the individual teachers as my unit of analysis, not the team.

In phase two, I attempted to identify the purpose and nature of the differences documented in phase one. I returned to investigate our Parachute Challenge planning sessions, interviews, and conversations in search of dimensions of contrast (Spradley, 1980) between the teachers, such as "explains first" and "communicates a right way to do something." Looking across these contrasts for consistencies and changes over time, I sought coherent lines of reasoning to explain the teacher's individual decisions.

Joining individual's attributes across domains, I tried to find patterns of thought and action for each teacher to articulate the emerging characterizations of the differences between them. To name the differences I saw, I used various markers of individuality, like beliefs, motivations, feelings, pedagogical content knowledge, physics content knowledge, epistemic stances, and other markers identified in bodies of research. I made several false starts weeding through these lines of reasoning, trying to use various epistemologies of engineering to explain wide swaths of observed phenomenon.

I found that the teachers' different choices were almost always well-adapted for at least some kind of instruction, but not always for engineering-design instruction. It seemed as if their decisions had alternative productive purposes, and I finally decided I would like to point those out. It's not that these teachers struggled in engineering-design instruction because they were somehow inadequate, lazy, or ill-intentioned; they just had other instructional methods and goals that didn't happen to align with engineering design, such as providing easy, scaffolded laboratory experiences and directly teaching the factors that affect air resistance.

This dissertation attempts to paint a rich, descriptive picture of some of the difficulties of integrating engineering into these teachers' classes. It is messy, but I have resisted cleaning it up artificially. I want the reader to recognize just how messy authentically integrating engineering design can be. It is confusing and complex to do; the teacher must at once be learning and teaching, and might have little time to deal with the mental conflicts that arise.

4.4.1 Positionality Statement

My viewpoint as a researcher has been influenced by my experiences and identity. I am a 35-year-old white woman from a privileged background. I majored in physics and sculpture and believe that making objects can lead to learning about the physical world. I value student creativity and independence, and I find beauty in simplicity. Although I am not an engineer, I brought expertise in thinking about engineering integration, having worked on that task with the Knowles Science Teaching Foundation's Lever Engineering Group for the past six years. I also had participated in the University of Maryland Engineering Education Research Group (EERG) and had taught and supervised pre-service teachers in an NGSS state.

Finally, I had taught at Merlin for five years, which at once provided me helpful access to the school, and also meant I had institutional knowledge and influence that, combined with my status as a PhD student, impacted the teachers' perceptions of me. All three teachers variously said they were nervous to have me in their classrooms when the study started. Leslie said that she thought I was an authority on engineering integration, and she was concerned about getting the engineering design "right" in front of me. I worked hard to not be domineering in planning and conversation, and to discuss and validate all of the teacher ideas, adding in many of my own, to show that many ways of thinking were appropriate, not just one.

Over time our relationships became comfortable and congenial. Eventually the authority dynamic normalized, and the teachers said they wanted to share what they'd learned about engineering-design integration. Anna wanted to speak at a county-wide teacher in-service meeting, Katniss wanted to share engineering design ideas with her IB planning group, and Leslie wanted to work with other local and national teacher groups concerned with engineering-design integration.

4.5 Mini Portraits: Inquiry Facilitators

The Parachute Challenge involved integrating engineering design into these teachers' usual inquiry instruction. To understand what was added or removed, this section introduces each teacher's non-engineering methods of instruction, their laboratory practices, and inquiry instruction.

4.5.1 Leslie Encouraged Student Discovery

Leslie tended not to give many directions to her students in her non-engineering physics instruction. Instead, she used various methods to reduce her responsibility in the classroom and shift authority to technical experts, students' peers, or the students themselves. For instance, in labs she preferred to use level 2 ("guided") or 3 ("structured") inquiry instruction (Rezba et al., 1998), providing well-organized materials and clues for using equipment, such as technical equipment specification sheets. She once told me about students doing a less frequent level 4 ("open") inquiry investigation into "something about spaghetti." When some students declared that they would burn the spaghetti to find the energy present, Leslie was excited by their idea! She loved that they had thought of a way to learn something by doing science in a novel way.

Leslie also valued student authority and expressed this value by frequently requiring students to make decisions for themselves, which at times frustrated students. In whole-class discussions, she encouraged students to come to consensus and to use that consensus as approval instead of her, the teacher's, judgment. Leslie required students to justify their thinking with well-collected data, trusting both student lab skills and empirical data to help teach content physics from inquiry investigations.

4.5.2 Katniss Routinized Inquiry

Like Leslie, Katniss employed level 2, 3, and 4 inquiry but seemed to trust the inquiry process and student reasoning slightly less than Leslie overall. Katniss took a more “paint by numbers” approach to inquiry and sense making. She wanted students to experience the fun of stepping into the unknown and taking risks (risk-taking was one of her personal goals for the year), but she also took care to scaffold and structure the process and the conclusions. For instance, Katniss encouraged open inquiry projects with her IB students but required each student to meet individually with her to discuss their plans, and sometimes to revise them, before conducting any experiments. Katniss did not want students to ever have a null result and would subtly rework an open inquiry idea with students so that they might achieve some measurable result.

In regular physics, Katniss similarly wanted the students to achieve very specific results, so at times she would even fib about what questions students had asked her in order to create an opportunity to address issues she knew could be problematic. When students presented their results, Katniss wanted to see claim, evidence, and reasoning, but would accept a repeat of her own reasoning presented in class as evidence that a student has reasoned.

4.5.3 Anna Ensured Success

Of the three teachers, Anna seemed to feel most responsible for student learning and did not always trust scientific inquiry to do the job of teaching for her. So she frequently worked closely with students in the lab while facilitating level 2, 3, and 4 inquiry, helping them craft questions, showing them examples, and at times actually interpreting their data with them. When students struggled at sense-making in the lab, Anna suggested hints and tricks for interpreting data and pointed students in specific directions even when inquiry was supposed to be more open. Anna always supported students decisions and gave her full attention and care to the students, but frequently she pleaded with them to change their direction and steered students towards inquiries that she was familiar with or that she was sure would support conclusions she had planned on.

Anna did not have a physics degree and said she still felt less comfortable with physics than with other sciences like biology or earth science. But Anna made up for her discomfort with careful diligent preparation and planned scaffolding. Anna’s objectives were always clearly posted on the front board to avoid confusion and to orient her students for the task at hand. Anna rehearsed lessons before teaching them for the first time, prepared and peer-checked an answer key for practice problems, completely conducted student labs herself before assigning them (even if she’d taught the lab before), and provided an example for students to reference for almost every project or presentation (e.g., a completed student whiteboard for whiteboard presentations, or several past students' iPhone cases, roller coasters, and musical instruments, or just an inspiration cart to get the juices flowing).

These efforts helped Anna make sure that everything was clear and achievable for the students. Her efforts broke down walls of student fear and disillusionment and were intended to ensure student success. Anna's rehearsals, objectives, and examples also ensured that she confronted her own misunderstandings and had a better understanding of how elements of a lesson combined to make sense of physics.

4.6 Parachute Challenge Background and Summary

The Parachute Challenge was co-designed by the three teachers over two weeks to introduce and scaffold engineering design into their physics curriculum and to teach concepts of terminal velocity. The teachers planned to teach the challenge before their winter break in December. All three teachers had first been exposed to the engineering design process in an after-school professional-development session that I led in early October. After that, I had numerous conversations with the teachers, both separately and together, about engineering design. Leslie had planned and executed the Pumpkin Chunkin' Challenge in November (see Chapter 5), and Katniss had brainstormed an engineering design challenge for her IB class, although she had never used it. Anna had not yet planned an engineering design challenge.

Katniss was eager to begin planning, so eager that she and Anna met once even before the planning meeting with Leslie. This was Katniss's first attempt at teaching engineering design because she had skipped Leslie's Pumpkin Chunkin' engineering design challenge. Anna wasn’t quite as excited as Katniss, but she was being a team player. Anna had previously tried teaching Leslie’s Pumpkin Chunkin’ Challenge, but it hadn’t gone well. Anna just didn’t feel comfortable in her first attempt at that lesson and ultimately did not attempt the activity with all of her classes.

Leslie was emboldened by the excitement her students felt when they completed the Pumpkin Chunkin’ Challenge, and she felt she had reached a better understanding of the engineering design process by having planned and taught that challenge. Now she was also eager to plan with her colleagues after having planned the Pumpkin Chunkin’ Challenge on her own.

4.6.1 The Former Coffee Filter Lab

The previous year’s Coffee Filter lab was designed to be the student’s first introduction to forces after kinematics. In it, a coffee filter fell, and the students plotted its motion on a position-versus-time graph using video capture technology and motion mapping software. The basket coffee filters had a low mass-to-surface-area ratio, and achieved terminal velocity within the space of a few meters. This lab set up a discrepant event to “motivate” a need to discuss opposing forces. The coffee filter doesn’t fall with the acceleration due to gravity ($-9.8\ m/s^2$) as students expect from kinematics; instead, it mostly falls with an acceleration of zero. Later, the teachers revealed that the steady velocity reached is called “terminal velocity,” and later still the students were asked to explain for themselves what might be causing this terminal velocity (a balance of forces on the object). Students were expected to draw conclusions about forces related to motion, before studying balanced and unbalanced forces, free-body diagrams, and Newton's Laws.

The expected results weren't given to the students ahead of time. However, the teachers defined the lab's research question, and the steps for completion had been clearly laid out. So it was a level 2 ("structured inquiry") lab.

The lab process was not difficult per se, but it was very time consuming to tag each frame of the videos. Each student group only had time to tag and examine one drop in a 90-minute class. Even so, the lab "worked" consistently. Students saw the zero-acceleration graph and recognized the discrepant event, which caused them to reason that something in addition to, or opposed to, the force of gravity was also acting on the filter.

When the teachers approached the lab anew as an engineering design challenge, they were concerned about losing the content acquisition for the sake of trying engineering design, which led to the first tension of adopting engineering design reform, a tension between separating out physics content and truly integrating engineering-design instruction into physics as envisioned in the NGSS. To create an opportunity for more data collection, the teachers realized they would need to use an alternative data collection method, which led to the second tension, a tension between data collection constraints, such as time and technical expertise, and adequate data collection for making design decisions. The notion that students needed to work divergently and independently led to the third tension, a tension between teachers' supportive classroom routines and allowing divergent student thinking and agency.

4.7 Emergent Tensions with the Parachute Challenge

This section discusses each of the three tensions. For each, it discusses how the tension appeared in planning, and how it later played out in classroom implementations.

4.7.1 Tension #1: Emphasizing Engineering Design Versus Physics

In agreeing to teach the Parachute Challenge as an engineering design challenge, the teachers faced a need to balance content physics instruction with engineering-design instruction. Each teacher seemed to have different expectations for how learning physics content could fit into the lesson. Analysis of this issue identified an underlying reason that these elements might be in tension: the teachers each conceptualized engineering design as different from physics learning, and they were variously concerned about forfeiting effective physics instruction if they tried engineering design.

4.7.1.1 Planning the Challenge

The goals for the lesson were (1) to use engineering design in physics class to allow students to learn about what engineering design is and what processes are involved; (2) to teach physics content about terminal velocity, including investigating terminal velocity graphs to illustrate that terminal velocity is not quadratic but is linear (a discrepant event) and then asking students to reason that acceleration is zero not $-9.8 m/s^2$ so some other force(s) must be acting on it in addition to gravity; and (3) to have students learn what factors affected terminal velocity and what the effects were. How the teachers initially envisioned balancing these goals came out in our three planning sessions.

The teachers started planning with the idea that students could engineer a parachute to fall as slowly as possible. If falling as slowly as possible was the major criterion, then the students needed a way to measure which parachute fell the slowest. Anna suggested using video capture because that would not involve the time-intensive dotting to determine which fell the slowest; students would just need to scroll the timeline of a slow-motion video to find the duration of the fall.

Katniss liked Anna's idea because it would take less time per fall to gather data than dotting had. It would be an engineering design challenge, and students might still learn about the changes to a filter that could slow its fall (surface area, mass, materials, etc.) Leslie disagreed because this data-capture method would not involve analyzing a graph of the fall or identifying the constant velocity and zero acceleration markers of terminal velocity during the drop. Using video capture would remove the practice of graphical analysis to understand the kinematics occurring and eliminate the discrepant event previously relied upon to motivate the students' leap to conclusions about forces in terminal velocity.

Leslie suggested using a sonic motion detector. It could create position-time graphs in real time, and students could take measurements of velocity, acceleration, and thus terminal velocity from the graphs. Scaffolding the motion detector's use would take more time than the video and timeline method, but Leslie thought she could afford that time because her students had already been introduced to engineering design in the Pumpkin Chunkin' Challenge (not to mention that she feared difficult lab facilitation less than Katniss or Anna did; see section 4.7.2). Leslie explained to us that she was willing to shift her emphasis away from scaffolding the engineering design and toward terminal velocity because she thought her students would be able to use engineering design since they had seen it before.

Leslie: I think that there [are] two different games that are going on right now: One is content, which the kids can get through—the kids semi-already know. We haven't necessarily matched graphs to terminal velocity yet, but they can look at a graph and they can say there is zero acceleration there. They just don't yet have the leap of zero acceleration equals terminal velocity. [Katniss] can make that happen super quick if her priority is introducing this design concept that we [(Leslie and Anna) already] did with catapult project.

> This brainstorming session that you guys had with just timing it [using the video capture method] is going to be a really great way of intro-ing kids to the design process. It is missing the piece of really laying terminal velocity on thick, which is what I really value because I've already introduced kids to design. So I think that, if I did this project as is, my kids would be like, "What the heck? We just did this." There would be not as much contextual meaning. That's really the deep,

> deepest part of it, that there wouldn't be as— I really want to get into terminal velocity if I can because they already have the design process. So I want to like bring it even deeper with them in a context that we're about to start talking about anyway.

Here, Leslie restated her goal for this lesson, which was for students to begin to understand terminal velocity conceptually in terms of forces and Newton's Laws by reasoning through the balanced forces acting on a coffee filter falling with zero acceleration. She also said that her students were most of the way there already, referencing their skills at graph reading from the previous unit. Leslie assumed that because her classes had already done the Pumpkin Chunkin' Challenge, they would be familiar enough with the engineering design process that she wouldn't have to scaffold the engineering part as much. So she preferred to focus on understanding the terminal velocity concept.

Katniss understood Leslie and double-checked by rephrasing what Leslie said, but then she made a bid for marrying engineering-design learning and terminal-velocity learning, no matter what data collection method was used:

> Katniss: But I think that what you're saying is this [using the video timeline tool] is heavy emphasis on engineering design and less on terminal velocity, [and] intro [to] forces.
>
> Leslie: Because of that—whatever that DV [dependent variable] is.
>
> Katniss: Yeah, because of the time, because of using time instead of using actual graphs [to parse different accelerations]. So, what I would like

> to see is if we can modify this game plan that we came up with so that it's useful for me and somewhat [for] you, like, introducing engineering design but also married with content.

Katniss did not see a reason to separate out the two parts (engineering design versus content) or to cut one short because of time. Instead, she asked for commingled priorities, and was willing to revise the plan to get there.

Anna had a third take on it. She made a bid to parse out the two elements but only to make sure that they were both touched on separately, not to establish which one should dominate.

> Anna: I still like the idea of them having a design challenge and having it with the context of making a better parachute. Maybe we could just do it as two separate things: do the coffee filter [former lab] to introduce the idea of terminal velocity and forces, and then, like you said…have another day where we did do something and maybe we don't have graphs of it, but somehow they could quantify what makes a better parachute. So whether we have all the same masses and then you see which one is able to take the longest amount of time to get to the bottom. I don't know.

In her bid, Anna advised keeping the old level 2, structured-inquiry coffee filter lab and then doing a separate engineering design activity that would not demonstrate the falling body's acceleration but would instead use the total drop time as a measure of success.

This planning conversation revealed the different ways that the teachers conceptualized content and engineering combining in physics instruction. Katniss believed there should be a way that engineering design could be "married with content," Leslie was picturing a natural need for one having to take priority over the other, and Anna was picturing a separation between physics content and the engineering challenge to make sure the content was very clear and explicit before tacking on the engineering design challenge. Table 4.1 summarizes these three approaches.

Leslie	Katniss	Anna
You'd have to choose which of these you have time to emphasize. One will have to dominate. Engineering can practice content, but you should make the engineering process clear, too, and possibly before the content.	Marry them together. The engineering can teach content.	Content and engineering design should be covered equally but separately. These are best learned separately because they are separate ideas.

Table 4.1 Interaction of Engineering and Physics Described in Planning.

Leslie was usually comfortable with students constructing their own meaning from open-inquiry labs in physics. In this case, however, Leslie seemed to be suggesting that engineering design practices as a set of knowledge needed to be scaffolded separately and maybe before the physics content knowledge, which she would usually allow experiential inquiry to teach. She suggested Katniss needed to spend more time on the engineering process explicitly, but once taught, students would understand the process and would be able to use it again.

Katniss said she believed marrying content and engineering design could teach the content fully, and that agrees with her statement at our first planning meeting in October:

> Katniss: I feel like what this is [engineering design] you learn content through doing whatever project…If you're learning stress/strain you could test stress/strain and learn that empirically rather than like ok, we're going to teach about stress strain and then do this project while you…where you like demonstrate your knowledge, more so.

In both moments Katniss seemed to be taking a more trusting approach with engineering design than she usually did with physics inquiry. She seemed to be trusting that the engineering design process can scaffold and structure the learning instead of the teacher.

Anna seemed happy to separate out the parachute activity she'd used before to teach a discrete physics concept (terminal velocity) from the engineering design. Anna was usually the most scaffolded of the three teachers in her instruction, and separating content before process aligned with the scaffolding she usually did. Maybe she believed students would have to learn this discrete concept the correct way anyway, so why not make sure of that before complicating things. Or maybe Anna prioritized the engineering design aspects of the activity less. However, I think it's more likely, based on her other inquiry instruction, that Anna was just interested in keeping things simple for the students so they could have an easy time in the lab.

After recognizing and stating their different perspectives, the teachers negotiated more and decided to introduce terminal velocity via a warm-up about graphical patterns, before introducing the engineering design challenge. The warm-up (see Appendix 4.1) was constructed to lead into the challenge by scaffolding graphical interpretation including explicit identification of the section where the filter fell in terminal velocity. They also agreed to use the graphs in the engineering design challenge instead of using the less content-heavy video-timeline idea.

This compromise reduced the level of inquiry in the challenge; students would not “discover” that terminal velocity has zero acceleration by analyzing experimental graphs. Instead, they would be told to look for zero acceleration (constant velocity) and where to look for it. But students could still explore physical aspects of the coffee filter related to terminal velocity without explicit instruction on the air resistance equation, and they would still have a chance to puzzle out why that occurred, motivating the need to discuss forces.

To make sure the students identified and analyzed the terminal velocity section on their graph, the teachers drafted and suggested three acceptable criteria for the challenge: time to reach terminal velocity, time in terminal velocity, and speed in terminal velocity (see Appendix 4.2). During the challenge, students would brainstorm ideas for how to change the filter, pick one idea, and then test how that change affected the position-versus-time graph. By having three options for optimizable criteria, the students would retain some choice in the challenge’s main criteria, but all of these would still require practice with the terminal velocity graphs.

And significantly, all of them would lead to the same graph and then the same discrepant event.

4.7.1.2 Engineering and Content Boundaries During Instruction

Despite the compromise to use a warm-up to introduce terminal velocity graphs before examining effects on terminal velocity in the engineering design challenge, the teachers balanced content learning and engineering design differently in instruction.

Although Katniss made a bid to use engineering design to teach the terminal velocity content—a marriage of the two objectives—she scaffolded terminal velocity before the challenge. Her lesson followed the compromise model, and she used the warm-up to demonstrate terminal velocity directly before going into the challenge. Katniss had her students work independently, and then she talked through the warm-up using metacognitive modeling such as asking and answering her own questions, revising her work, and clarifying moments that she thought were confusing.

In the warm-up, Katniss deferred to her own authority to make sense of the graphs and to translate those graphs to students, explaining away bad data and expected confusions. Katniss made her words slow and deliberate, demonstrating the kinds of thinking she wanted them to do, including metacognitive thinking. Katniss made sure that the process for understanding the content was clear.

Anna separated physics content from engineering design. During the planning, Anna made two bids to separate the content learning from the engineering design challenge, but in the end she agreed to use the engineering design challenge to practice and deepen the content. In teaching, Anna went back to the separation idea. She did the warm-up and the graphical sense-making about terminal velocity five days in advance of the engineering design challenge, and her instruction in the challenge also supported a separation between doing the challenge and making sense of the physics.

On the day of the challenge, Anna reminded her students of what had happened to velocity and acceleration in each section of the warm-up's graph and focused them on the pertinent section, the third "chunk" before going into the skydiving challenge. Once into the challenge, Anna further guided her students' sense-making about the content goals, instead of allowing the physics content understandings to emerge from doing the engineering design. She told every lab group, one by one, to change the mass and look for resulting changes in the terminal velocity (in m/s), and she helped four of the six groups interpret their graphs and reason out recommendations to meet the challenge's goal.

With these changes, Anna ensured her students would do engineering optimization and learn the content, but not from or through one another. She made sure the students would see the discrepant event, see a relationship between mass and terminal velocity, and see optimization at work as the mass affected the terminal velocity through a narrowly scaffolded engineering design process that necessarily ignored any other potential factors influencing air resistance and terminal velocity. For instance, one group was decreasing the surface area of the filter by cutting it into smaller and smaller circles, but Anna told them to still make a graph of terminal velocity versus mass. Sure, they'd likely see a relationship there, but their growing understanding about air resistance would be limited to how the mass affected terminal velocity and wouldn't involve surface area.

Anna's approach to instruction implies that she might have felt some discomfort or unease with merging engineering design and physics, or perhaps she did not realize she was unmerging them by providing reasoning for her students. Perhaps it seemed to her that the students had too much to worry about at once, so she gave them a break. But Anna definitely did get to both the content and to the engineering, just not in as integrated a way as the teacher team had planned. (Section 4.7.3 explores what Anna's decisions in this lesson meant for student choice and authority.)

Leslie sought student sense-making in the context of the challenge. In planning, Leslie advocated for backgrounding the engineering design process and highlighting terminal velocity as related to skydiving. So maybe it makes sense that in class she allotted considerable time (18 minutes) to student-centered sense-making in the terminal velocity "chunking" warm-up before turning to the engineering design challenge.

While Leslie's students started the warm-up in their groups, she took attendance and wrote all of the question numbers and blank graphical axes on the whiteboard. Then she quietly went around to tell each group which problem they were responsible for putting up on the board. When the solutions were on the board, she said, "I see a lot of different answers for things as I walk around. So we all need to be very focused on, um, the discussion on this warm-up ‘cause I don’t see consistency across the classroom. So that means there’s going to be some that are correct and some that are incorrect.” In this warm-up Leslie followed her usual pattern of requiring students to do sense-making without direct teacher guidance. She provided the opportunity for the groups to work independently and deferred her authority to that of the class by asking them to agree on all answers. When she helped a group, she encouraged a productive struggle by not giving away answers. (See more on student agency in section 4.7.3 below.)

When Leslie introduced the skydiving challenge, she asked the students to think about how opening a chute too early or too late would affect the competitor’s success before getting into the goals of the challenge. Student questions and class conversation touched on the dependent variable options that the teachers selected earlier, before mentioning that the students would be optimizing coffee filters. Leslie engaged the class in enthusiastic sense-making about terminal velocity, saying, “Oh, this is so good, guys!” and “great great great great great” throughout the discussion. My field notes captured an illustrative interaction:

> Leslie: What’s a way that they can maximize [skydiving contest] points the fastest?
>
> Student in front: [They can] stay in terminal velocity the longest.
>
> Leslie: I don’t know how you’re going to be in terminal velocity the longest
>
> Student on right: He has to achieve more air resistance to slow down.

[Students have many ideas about this, and there’s a lot of chatter. Leslie allows the chatter.]

Student on right: Are they not allowed to wear wing suits?

Leslie: Why might they want the lowest terminal velocity?

Student “Red”: More time for moves.

In this example, the students brought in ideas about slowing down, air resistance, and terminal velocity. In other moments, the class discussed how the skydivers get together on horizontal planes while falling, and students brought up changing their surface area and squirrel suits again. Perhaps all this discussion of factors affecting air resistance in the context of terminal velocity was more activation than content learning. Still, the students had an opportunity to reason out some of these factors before stepping into the engineering design challenge about the coffee filter.

Leslie was not focused on just the physics content (terminal velocity) or just the engineering challenge. This skydiving discussion was focused on both the content and the structure of the skydivers, and how they were coming together in the phenomenon of skydiving, including what body positioning has to do with anything and whether squirrel suits might be allowed. She was allowing a sense to build, even before introducing the challenge, that form affected to terminal velocity, and that how an object slows down might depend on its physics characteristics.

Overall, Leslie mostly focused on student sense-making in the context of the challenge. Though she initially said she would background the engineering design, what she diminished in instruction was not the engineering design process, but rather her direct instruction of the engineering design process.

4.7.1.3 Striking a Balance

Stepping back to better see the structure of this issue, we find that, in planning, the teachers each advocated a different relationship between doing engineering design and teaching terminal velocity. Though they found and drafted a compromise solution, in instruction Anna returned to the clear-cut separation she originally desired, Katniss left her initial "marriage" interest to really hammer out terminal velocity before the design challenge, and Leslie integrated the content and context of the design challenge by engaging students in terminal velocity sense making in the context of the challenge instead of letting one or the other dominate.

Leslie	Katniss	Anna
In planning: You'd have to choose which of these you have time to emphasize. One will have to dominate. Engineering can practice content but you should make the engineering process clear, too, and possibly before the content.	In planning: Marry them together. The engineering can teach content.	In planning: Content and engineering design should be covered equally but separately. These are best learned separately because they are separate ideas.
Planned compromise: Introduction to "chunking" procedure planned as a warm up.		
During instruction: Sought student sense-making in the context of the challenge, let them go on their own.	During instruction: Scaffolded content separately during warm up, then got into the challenge.	During instruction: Separated the content from engineering challenge by a weekend, assisted analysis.

Table 4.2 Interaction of Engineering and Physics in Planning and Instruction.

In other words, the tension between engineering design and physics content instruction persisted. Even though the teachers seemed to reach a compromise, their individual interpretations during actual instruction revealed that they were each still dealing with the tension differently.

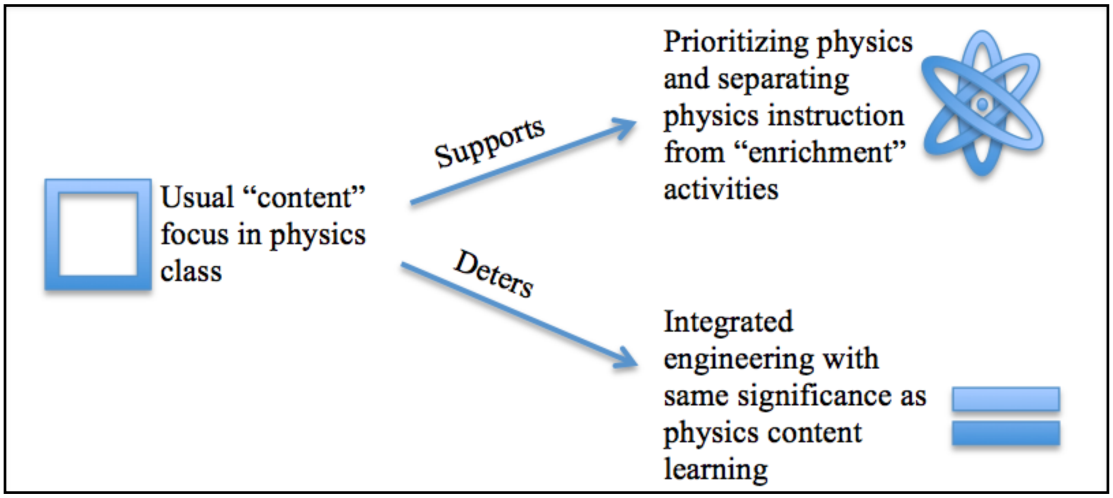


Figure 4.3 Tension #1: Emphasizing Engineering Design Versus Physics

4.7.1.4 Discussion, Tension #1

My purpose in describing the teachers' three different conceptions of how to relate engineering design to physics content is not to compare their value. None of these three are better or worse ways to think about engineering-design integration in high-school physics; all of them are valid ways to do engineering design with physics content. Instead, for reform implementers, PD writers, and teacher educators, this example—providing three models of how content and engineering-design integration might look—provides a starting place for discussing variations in teachers' methods and in the complexity of integration. The teacher's reasons for separating the content instruction from engineering design, or not, will be explored further in tension #3 (section 4.7.3).

Reform writers must specify what kind of integration they mean when they said, “understanding engineering practices can help students acquire and apply science knowledge.” Did they envision more or less well-integrated instruction? What is good enough? If recommendations for K-12 engineering are rooted in higher education’s history of engineering design, then they are necessarily rooted in a tradition of separate content classes and engineering-design classes. Unpacking the distinctions between that history of separation and what is required here would be useful, including a more consistent and intentional usage of “engineering design” versus “engineering.”

Dare et al. (2014) found that many physics teachers failed to use or mention content in engineering design challenges. In my study, the Merlin teachers included engineering design in their content instruction, but they separated content and design in various ways. Now that I’ve seen various possibilities for highlighting engineering design or physics content within the same lesson, I wonder if the Dare study simply did not recognize or validate the many ways that teachers might arrange their physics and engineering-design instruction priorities, including by foregrounding one or the other, using one to bring out the other inductively, or marrying them together.

In prior research (Dare et al., 2014; National Center for Engineering and Technology Education et al., 2009), the issues identified for integration did not include those related to the preference of sequencing or emphasizing engineering design versus or over content. My study reveals that teachers not only struggle with how to prioritize engineering design and physics content, but that their plans for, and execution of, engineering integration can be different. The three teachers' implementation of engineering-design integration varied more than I expected it to for such a tight-knit group of co-planning teachers who had discussed their conceptions of engineering design versus content teaching and reached a compromise. These three teachers collaborated so well and so often that it I assumed that they wouldn't differ in fundamental ways as to whether an activity portion of a lesson can be used to teach the content in a lesson. Though the group was tight knit, co-planned this lesson, and even enumerated their differences during planning, significant variation occurred in instruction, with teachers separating content from engineering design processes to different degrees.

At times, the teachers' individual decisions in engineering instruction seemed consistent with their decisions or descriptions in other frames, such as inquiry instruction, but at other times inconsistent. In watching their other problem-based learning (PBL) and inquiry physics teaching, I assumed they completely agreed about whether the activity was teaching the content, was overshadowing the content (i.e., was subordinate to the content), or was just a fun example of the content. It could be that they had better agreement in those familiar physics lessons and labs, but that their expectations diverged in this new engineering-design integration experience.

I am curious about why Katniss seemed initially confident or trusting that engineering and science could be "married" together. Just what or whom she trusted is worth considering. Maybe she trusted the NGSS because the NGSS says it should work that way; maybe she trusted me as her teacher-mentor and the groups I represented (academic university research groups and teacher-led engineering integration groups); or maybe she just trusted the authority of “engineering” in general because she knew engineers were trained to solve problems, did hard work, and were paid well. The data here does not justify picking one of these conclusions over the others, and more research would be needed to understand why she made her initial NGSS-aligned “marriage” assumption.

The next two tensions emerged as I observed the teachers help their students make sense of data. Tension #2 concerns data collection, and tension #3 concerns design decision scaffolding, including data analysis.

4.7.2 Tension #2: Constraints of Data Collection Versus Adequate Data for Design

Using data to drive engineering decisions is a key part of improving a design. The teachers knew that, to improve the “parachutes,” the students would need to have clear data that they could understand and have enough data to make quick prototype (design phase 2) decisions and more controlled optimization (design phase 3) decisions. (Recall that this issue emerged at the beginning of planning in Tension #1 above.)

4.7.2.1 Planning: Data Collection Methods Caused Concerns

The teachers decided to collect data using a sonic motion detector mounted above the falling object because the detector produced a position-versus-time graph for the falling object in real time. However, Katniss was very concerned by two issues. First, sonic motion detectors produce fairly "messy" data with lots of erroneous data points because the sensor "sees" data from sound reflected from other, nearby objects. Second, students might not be able to pick out the points on the graph where the acceleration changed because identifying the trends well and quickly requires practice and also requires skills like trying curve fits and resizing the graphs.

These technical difficulties were not Katniss's only concerns, as discussion soon revealed. Katniss was also worried that because the data collection technique was new and messy, she would need to do extra hand-holding or "putting out fires" during the lab in order to help her students use the collected data appropriately to guide terminal velocity optimization (highlighting appropriate data segments, and picking out changes in slope, etc.). Running around "putting out fires" would not only cause her stress, but would also require significantly more time for multiple one-on-one conversations than she had previously allotted in the old Coffee Filter lab. Also students were supposed to do multiple rounds of iteration, and this additional data collection was sure to take additional time. Katniss expressed her concern in the planning session,

> Katniss: I do worry though, like even when I do this sort of thing with IB, I'll kind of have to go around and help them with the y-axis scale…I'll have to help them…Like I worry [with the General Physics course] that the Logger Pro skills aren't there, and that I would be running around trying to show everyone…That's what I did for IB, and it still

> was like putting-out-fires sort of thing. So I worry about the technical skills if the goal is to kind of do these [rapid prototype drops] quickly and get the results. I don’t think this is as quick as we’re thinking.

Here, then, was an opportunity for students to practice pattern-finding, but Katniss was worried her students wouldn’t be able to find the transition points in the graph between the patterns. She compared the skills of her target audience (general physics students) to the skills of her IB students again two days later, saying, “Picking out what the patterns are, and then picking out what’s a good [end point], what data would be a good to get your fits on was difficult” for her IB students; and if they had a hard time, then she was certain the general physics students would also have a hard time. When Leslie and I tried to assure her that her students could do it, Katniss said, “I just do not perceive this going as well as you guys are describing.”

This engineering design challenge required students to collect lots of data quickly to optimize their designs, but because the fastest data collection technique was messy and might require lots of teacher assistance, Katniss was feeling a tension: available class time and the technical constraints of the data collection method came into tension with the need to collect adequate data in multiple iterations for students to do authentic design decision-making.

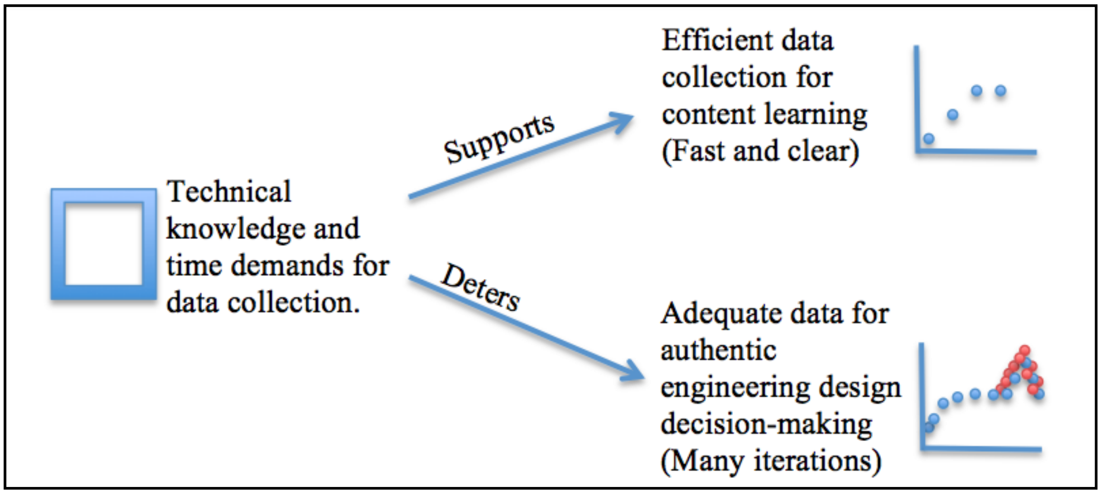


Figure 4.4 Tension #2: Constraints of Data Collection Versus Adequate Data for Design

Another teacher feeling this tension might have thought, "It is okay to simplify the data collection I require so that it can be collected in one day to reach a specific content goal efficiently." This simplification would help a teacher keep the lab under control by providing the teacher with adequate time to assist each group and ensure that each group of students learned the science content correctly and quickly. A teacher who is accustomed to facilitating physics labs in this way (like Katniss) might not want to add in multiple iterations of data collection because they'll have to give even more guidance for each round (lots of teacher work!) or risk that the data collection might not lead students to learning the content goals. On the other hand, helping students take and interpret a limited amount of data slowly might help students learn the targeted physics content (about terminal velocity) in a more controlled and direct way, but that approach would not provide an opportunity for students to take multiple rounds of data to iteratively optimize their design.

This tension first appeared for Katniss in planning, but in instruction she was able to scaffold the collection process in a simple routine so that adequate data was collected. Anna on the other hand, seemed less concerned during planning but ended up providing scaffolds during instruction to ensure that data collection and interpretation led to clear conclusions even though she sacrificed authentic student-centered data collection and sense-making. In contrast, Leslie employed other methods for assisting students in the lab without reducing their decision-making experiences. For example, Leslie regularly used technical data sheets taped to the equipment to provide students with lab help as needed. Also she described how she "jigsaws" technical expertise in the classroom during planning:

> Leslie: It [the motion detector data collection] should be fast, and you might have to say, [to] this team, "When you get a graph, stop. I want to come over and talk to you about it." And then if anyone else is doing this [at that stage at that point] you pull one representative from each [group] and you go, "Look here, let's just talk about where you're going to take your data. [That's] what that's going to look like." And then you send them back and then they're good to go.

In the end, Leslie, Anna, and I convinced Katniss that it was worth the risk of difficult data collection to be able to gather the data necessary for optimization. The warm-up was created primarily to deal with the difficulty of data collection; after the warm-up, the teachers hoped the students would be able to analyze a Logger Pro graph and be able to choose "clean" sections of data to highlight for the terminal velocity “chunk.” Leslie also made a “Logger Pro Cheat Sheet” to help with these concerns. All three teachers were nervous about the live drop yielding a frustratingly messy graph, so they practiced and practiced, and they had a backup graph saved just in case.

4.7.2.2 Data Collection Tensions During Instruction

So how did it play out? This section describes how the teachers actually balanced the need for adequate data collection to drive decisions against the difficulty of dealing with messy graphs and taking up a lot of instructional time.

Katinss scaffolded her students to successful data collection in spite of her initial reservations. On the morning of the Parachute Challenge, she tested out the eight lab setups several times and was feeling chipper and confident about the quality of graphs she was making. The cleaner the graphs, the less she’d have to guide students in the lab. Knowing how afraid she was of students needing one-on-one support during the graph analysis later in the lab, it was no surprise that she was very intentional and deliberate when instructing them on how to separate the motion detector’s graph into “chunks.”

Katniss made graph analysis as simple as possible. She talked through her “chunking” method, asking questions aloud to herself about which data should “count.” She glossed over a bit of messy data in her warm-up graph, blaming the blip in the tail of the graph on picking up the coffee filter from the floor. She demonstrated how to zoom in using the software, and how to read the data table to find elapsed time more precisely. By holding up a meter stick to the board to show where the graph “peeled away” from the line of best fit, she demonstrated “right” and “wrong” ways to draw a line of best fit in order to find terminal velocity

Her preparation and scaffolding seemed to pay off, or else graph interpretation wasn’t as difficult for the students as she thought it would be. When the students were in the lab she was no more frantic than usual, and they gathered their testing data with little difficulty. Katniss spoke with each group and did some reminding, but she seemed at ease and let the students run their tests without micromanaging them.

By structuring the warm-up so solidly, demonstrating with the actual equipment, and instructing the procedures thoroughly, Katniss seemed to avoid potential “putting out fires” stress in general. The students did well and took adequate data within the time limits of the class. Without knowing how their data collection helped them achieve the instructional goal of understanding terminal velocity, I can say that Katniss seemed satisfied by the level of content learning that happened as a result of the challenge.

Two months later, Katniss recalled that the students did the warm-up problem with the erroneous data “very well” independently, but she also remembered that the blip in the graph stressed her. If she had it to do all over again, she said, she might leave out the process of scaffolding the blip because it wasn’t that useful and because actual irregularities in data collected required more reasoning than this blip prepared them for.

Katniss: I remember, I cut it off and said “Oh, it hit the floor, and then I pulled it away” to explain [the blip]. I remember, I think it was [Leslie] did the, “Oh no, that’s just a glitch in the graph. It really keeps going” or something like that. I remember feeling like next year I just want to remove this [blip] altogether and not deal with it. I think that their understanding of these things, how to find these three times or velocities or whatever, was still totally fine with or without this. Why not remove it and be less stressful for me?

Katey: Did it serve any value in looking like what they might run into?

Katniss: I think when they got to it, it was pretty apparent when they were pulling away on the graph. Things got crazy on their graphs and Logger Pro, crazier than this. Much more apparent than this. I think leaving it in, there’s no real benefit to it.

Leslie backed off during the lab and allowed students to make decisions for themselves. Just before her first attempt at the warm-up, Leslie was annoyed that she couldn’t get a reasonably clean graph. She wanted to make and “chunk” a graph live, in front of the students, not just analyze the graph on the warm-up page. At this point, it seemed Leslie was thinking that as long as the data came out reasonably clean, she trusted that the students could interpret it.

Leslie framed the entire warm-up activity as a review of kinematics by graphing, and asked each group of students to put pieces of their answers up on the whiteboard and then defend their answers. During Leslie’s warm-up, she only talked to one group and, in that case, did not give away answers. Once all the student answers were on the whiteboard, she told them all that there were a lot of errors, and she asked the class to reach consensus by arguing out each section or chunk and what it meant.

Looking at the blip in the pre-made graph on the warm-up, Leslie asked, “Why might that happen?” She took several student answers before asking the class if they thought the blip should “count” in the dataset or not. She and the students finally agreed that no, it shouldn’t count. Then she had them try to make a line of best fit on their papers, and afterward showed them how she would do it with a meter stick on the whiteboard.

After introducing the challenge, Leslie turned the students loose. She planned to show one representative from each group how to use the motion detector and then have them teach the other students, but she also taped instructions for data collection to the equipment in the lab. In sum, she used strategies to facilitate instruction and, once those were in place, she assumed the students had the ability to make sense of the graphs themselves. She didn’t need to put out fires. Instead she left the students to be accountable to one another.

Anna fought technical fires alongside her students during the lab. During planning, Anna had not seemed very worried about using Logger Pro. But during the activity, she became consumed by the feeling that there was an “easier” way to work with the data, and eventually she directed her students to use it.

Anna did not scaffold the warm-up during the class; she simply reviewed it because the students had completed the warm up five days earlier. When Anna’s students began to collect data, they hit a wall that Katniss had feared but avoided; the students struggled to pick appropriate start and end points for terminal velocity, and to parse out the quadratic from the linear section. (The students had been asked to choose one of the following optimizable criteria: time to reach terminal velocity, time in terminal velocity, or magnitude of terminal velocity.) Anna went around the room from group to group, showing students how to zoom in on the data and clarifying confusion about where to put brackets in Logger Pro. Anna was "putting out fires" of bad data analysis. Eventually she pulled me aside to describe why she was going to offer them more explicit direction.

> Anna: I almost feel like I want to tell them to use the slope. I just feel like that one's so much easier…I don't know. I just—I know the idea is for them to come up with a lot of this, so I hate to tell them too much but I do feel like that that's the easiest one to get good data.

After that, she revisited each group again and steered two additional groups towards finding the value for terminal velocity (the graph's slope) instead of their first choice, maximizing time in terminal velocity.

Anna had run into Katniss's early concern exactly. Student-designed data collection was technically difficult to achieve, and so Anna wanted to provide students with an easier procedure, to reduce confusion and make it easier to see "good data" trends.

Anna also encountered another technical difficulty in interpreting the results graph. The results graph captured the data collected in variable testing and enabled students to see if a pattern existed among the variables they were testing. The graph was drawn in the lab handout (Appendix 4.2). In this challenge, not all of the results graphs resembled the simple function patterns that the class had learned (flat line, linear, quadratic, or inverse); some had peaks, some fell off, and some flattened out. Anna went group to group and interpreted the results for almost every group to ensure that they made the right interpretation and to ensure that they reported the correct recommendations. To one group she said the following:

> Anna: Okay, so maybe number of holes doesn’t have an effect on downward—on speed? You could recommend not spending wasting money on putting perforations in your skydiving or having more space in between skydiving team. So as long as you can back up your statement give some evidence based on your graph you’re fine. Ok?

By helping students interpret their graphs, Anna pushed them toward the final requirement, a letter written to their stakeholder(s) about their recommendations, using claim evidence reasoning (CER) style writing. But she also reduced authentic student data-driven decision making and provided extra scaffolding to lead students safely to completion of the activity.

At the end of the lab, Anna was excited that the students had a graph and a conclusion to go home and write about. (Most of the letters to stakeholders would need to be finished as homework.) Anna congratulated the students for getting as far as they did, and she mentioned that in her last class students had been scrambling to finish data collection at the end.

4.7.2.3 Discussion, Tension #2

Tension between data collection and engineering design emerged for these teachers in two ways. (1) Katniss's planning fear became Anna's reality when a data collection technique that offered the ability to take enough data to guide design decisions also threatened easy, efficient data collection. (2) Concerns that students would not make sense of their results graphs accurately, or in time to write recommendations, led Anna to interpret results graphs and make recommendation for her students.

This tension between constraints and adequacy led Anna to provide students an alternative, "easier" data collection method. In almost any regular physics lesson, providing a clear data collection method would be a good idea, but, in this planned lesson, students were supposed to have picked out and followed an investigative approach to practice the science as they did the engineering design (i.e., endpoints-finding practice). Anna's decision to tell students to find the slope limited endpoint-finding practice and limited student choice. Later, when the results graphs did not match any known patterns, she assisted again by interpreting the results graphs for the students. This left little space for student struggle and reasoning, but it ensured they could finish the engineering design project completely and reach a reportable conclusion.

Taking data might seem like a minor instructional concern compared to figuring out what engineering design is and juggling epistemic shifts, but it is exactly the kind of problem that could prevent a teacher from trying real engineering design in a classroom. Either a teacher might not know how to collect enough data quickly to drive decisions in a feasible manner, or the decisions might not be driven by data. Either way, the engineering integration might not work as envisioned by NGSS if data collection is difficult.

We saw that working out ways to gather adequate data for authentic engineering design nearly prevented Katniss from even trying to gather appropriately student-centered data, and eventually denied Anna's students the chance to make their own decisions. If this kind of minor problem is almost enough to deter motivated teachers like Katniss and Anna from trying engineering integration, then perhaps engineering integration is actually not as easy as the NGSS portrays. Data collection techniques possibly should not be treated as minor aspects of a lab, because every technique's usefulness and ease can have a large effect on how much actual engineering design thinking students get to do.

4.7.3 Tension #3: Supportive Classroom Routines Versus Student Design Freedom

An important part of any engineering design process is generating multiple design ideas, and objectively weighing them against one another. Thus, engineering design requires the designer to think divergently, to be creative, and to test ideas for flaws and failure (Al-Atabi, 2014; Katehi et al., 2009; Petroski, 1992). Finding points of failure in a design is instructive, then, for how to improve the design and how to think about the problem differently (Petroski, 1992). But high-school instruction is almost entirely geared towards celebrating success (Al-Atabi, 2014), and so how can a teacher deal with letting, or even trying to make, their students “fail”?

In practice, authentic, divergent, student choice was in tension with the class structures and norms that supported relational comfort, emotional security, and efficient learning. The Merlin teachers began their planning with an ambition to incorporate student divergent thinking, and they planned opportunities for such thinking within the Parachute Design challenge (students would choose creative contexts, select optimization criteria, brainstorm designs and redesigns, design optimization tests, interpret test results, and make recommendations based on test analyses.) However, divergent student actions and the subsequent threat of failure soon caused the teachers to feel that their other relational, emotional, and teaching-efficiency norms were under threat. Katniss feared the students would head in too many directions during divergent moments, such that she wouldn’t know how to handle them in the lab and the learning might not be efficient. Anna feared student frustration, confusion, or feelings of failure because those reactions might stifle learning or betray a trust she was developing with her students. This led Anna to provide extra scaffolds to support and steer the students, reducing their opportunities for authentic engineering design and scientific inquiry. And yet, some things these teachers would normally do to support students, i.e., providing stiff scaffolds and clear directions, were in tension with engineering design values on divergent thinking and productive failure.

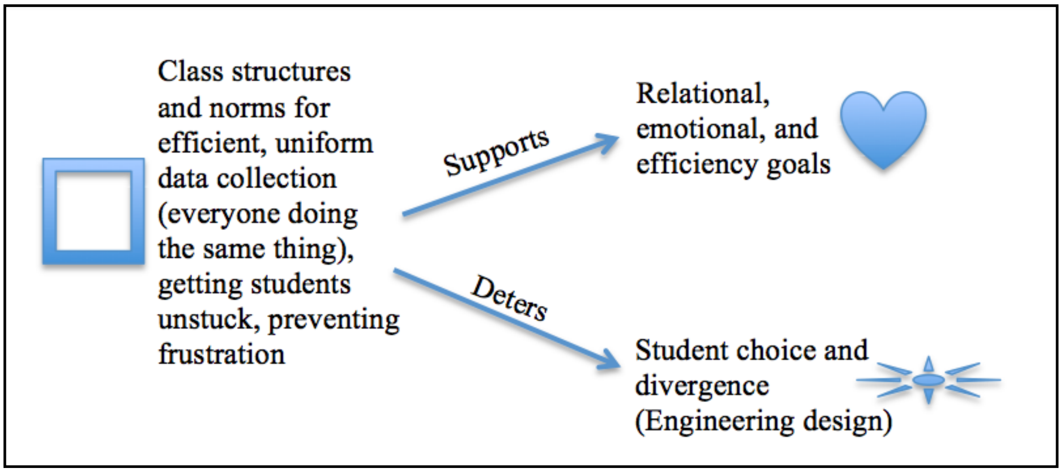


Figure 4.5 Tension #3: Teachers' Supportive Classroom Routines Versus Students' Divergent Design Thinking and Agency

The things that these three teachers feared are exactly the reasons that engineering design promotes divergent thinking. Heading in many directions means that the problem is being addressed in a variety of ways and the breadth of developed ideas is as wide as possible; and failure, at its most basic, is fundamentally necessary to move forward in engineering design (Petroski, 1992). However, it is important to note that these teacher's instructional decisions, while not engineering design-supportive at times, were entirely well-intentioned, underscoring again the point that even the most motivated and best-intentioned teachers could run into trouble with engineering design.

The teachers knew from our first conversations that engineering design, both as a whole and in parts, involved divergent thinking; so the planned activity offered several opportunities for such thinking. The planned challenge asked students to diverge in their thinking independently, as creative context inventors, as falling-body designers, and as optimization-test designers and interpreters. The teachers presented a skydiving team competition as context but allowed students to wrap their own creative context around it. Students were encouraged to think, “Why would anything want to fall slowly, and for whom would that be useful?” Setting the context and picking a goal were scaffolded on the lab handout. No matter what the students picked for a context, there was a small likelihood of student failure. Almost any hypothetical falling object would do, as long as the students believed the coffee filter modeled it.

To scaffold and quicken students’ design-related decision-making, the lab handout provided three optimization options from which the students could choose (time in terminal velocity, value of terminal velocity, and time to reach terminal velocity). Each could be found using the scaffolded data-chunking procedure with Logger Pro software, so each seemed to be scaffolded equally. The teachers thought that offering a choice among these three would increase student buy-in and also help students inductively develop hypotheses about how these traits were related. Any and all of these criteria being maximized would mean the same thing, that the object took a longer time to get to the ground. Depending on what the students picked for the goal, their data processing would be slightly different, but no choice would be significantly riskier.

Next, thinking up an optimizable design idea (via brainstorming) and inventing an experiment to test the design idea (on a given set of equipment) also offered divergent thinking opportunities and more chances for failure. Katniss expressed her concern in planning:

Leslie: But I think you're [Katniss] saying make a huge class list [to brainstorm possible parachute designs].

Katniss: I'm saying like, [in] patterns lab, [we brainstorm] what can we measure about this experiment? No?

Leslie: It's way more group individualized [in engineering design].

Katniss: Okay [unsure]

Leslie: It's really like, you being—you can just kind of let them go. You explain what needs to happen and you just let them go.

Katniss: And that's not like, like, —

Leslie: Oh it's chaos.

Katey: It's awesome.

Leslie: You're [Katniss] going to hate it so much.

Katniss: That sounds horrible.

Anna: [Laughs]

Katey: It's really like, student responsibility right? I mean, they pick up the torch and start running. And then you watch.

Katniss: I'm worried they're not going to pick up the torch. [Laughs]

Leslie: They will.

Katey: It's just fire.

All: [Laugh]

Katniss: [Conceding] Okay. So warm up, real life demo, cool parachute video to get them interested… .

Developing a design idea offered a great opportunity for divergence; but the students were all bound to start with the coffee filter, so it was already quite scaffolded. It was the same with the experiment. Although the teachers said students would design the experiment, students were told what equipment to use and how to use it, and they were functioning within the norms of physics classroom, too. Even so, Katniss was very nervous that it could slip into chaos.

By the end of planning, the teachers had designed a challenge that offered several points of divergence and required students to take on the responsibility to make their own decisions. They had a common lesson to use, but how these divergent thinking activities actually played out was different for each teacher. Katniss's nervousness and how it played out revealed a third tension, a tension between structuring students to ensure success through supportive classroom routines and allowing students to think divergently and make their own decisions in ways that are consistent with engineering design. Let's see how this came out in instruction.

4.7.3.1 Katniss Celebrated Divergent Thinking, Demanded More

Early on in discussion of teaching engineering design, Katniss expressed a fear of divergent thinking, saying, "I'm afraid they'll go a thousand ways." If that happened, she feared that she would be less able to quickly get testing factors related to air resistance and terminal velocity, like surface area, shape, and mass.

To prevent that, she worked the room during fourth period while students brainstormed their contexts, asking questions and laughing along with students, though at times her laugh sounded nervous. Students shared their refined problem statements, and Katniss repeated each one and placed their writer statements along the wall. I realized suddenly that Katniss was celebrating their divergent ideas and prodding them for more. She saw that they were not bouncing off the walls; they were just being creative. The boundaries and examples she gave had been adequate for the students to think up optimizable contexts.

Later, Katniss complained that the students hadn't gone far enough with their divergent thinking. In her second effort teaching this material, she said to the class, "some of these are very creative," implying that some were not. Later, I asked her to explain her remark that only some of them were creative. She explained that, for her, when students designed a context that was close to her set-up, human skydiving, even if it was a Navy Seal or Barack Obama skydiving, she felt disappointed in their lack of creativity. Instead she had hoped that they would translate the problem to a whole new context that still involved air resistance and drag. The teams who did that—such as air-dropped packages, babies delivered by stork, and runner-training parachutes—were more satisfactory to her.

As students developed ideas for their parachutes, Katniss allowed many dead-end ideas to play out instead of pushing students towards an efficient use of time. For instance, some students were determined to get their filter to fall like a dome instead of like a basket. They requested needle and thread, and Katniss scrounged some up. The students tried and tried to make a real-life looking parachute happen with the materials, and Katniss allowed and even encouraged their endeavor for the better part of 30 minutes. Katniss already knew that this real-life parachute idea was a losing proposition; we teachers had tried the same thing, and for longer, but never made it work. Yet she let them go for it, which shows she was okay with their trying some failing ideas.

Katniss demanded quantifiable design alternatives for optimization. She did maintain some of her usual scientific inquiry-oriented structures that might have limited students' divergent thinking; in particular, she insisted over and over that they keep their manipulations quantifiable. Later she recalled, "Quantifiable, like I don't want a group to go and investigate color. I'd be like, 'quantifiable.' " This did limit students' creative thinking, but it was appropriate for regular physics instruction, even in open inquiry. One can imagine that in a truly open design studio, the design alternatives might be looser or more open-minded, valuing a wider range of possibilities and weighing them in a complex set of trade-offs. But Katniss was tethered to her physics practices and felt that qualitative variables, like color, had no place in the lab.

Another teacher might not have demanded quantifiable variables or might have allowed students to change the color, and see that there was no effect. If changing the color actually did change the terminal velocity curve, then the students could have thought deeply about why and maybe made some logical connections to terminal velocity. Maybe coloring made the filter more massive or sealed the filter's surface.

Katniss was worried about student divergence during planning, but in the lesson she celebrated contextual creativity. Katniss seemed to be persuaded by teaching the planned divergent thinking in phase 2. Perhaps she saw, in the moment, that student creativity did not affect her lab goals, and so she began to allow more design divergence.

Anna provided scaffolds that reduced engineering design authenticity. She had not seemed very nervous about student choice when we planned this challenge. But as she spoke to the class in first period, she seemed to get more and more anxious, pausing and gathering herself several times. Anna instructed the students to design for the most time in terminal velocity even though their paper had three options of what to measure. In a span of four minutes, Anna seemed to go from confidently describing all three elements as different elements of the same thing, to advocating for just one element, time in terminal velocity.

> Anna: So that is really what we're going to be [exhale] thinking about [exhale] when you guys [pause] design [pause] your [pause], when you do your design challenge. ‘K so, you’re going to, [pause] be getting together with your groups [exhale], and you’re going to be thinking about [exhale] what your challenge is, okay, so you want to increase that time in terminal velocity as the skydiving team, so the skydiving team can have as much time as possible, um, doing their moves.

The students headed off to work in their groups, and Anna went from group to group, talking, listening, and reminding them what she meant by “role.” She offered a few examples repeatedly, “You could be a skydiving consultant, or a captain of a skydiving team,” she told each group in turn. After about 20 minutes, Anna began to provide even more concrete recommendations for some groups. For instance, 30 minutes in, Anna told one struggling group, “You guys are going to be, you’re going to be consultants, ‘K? [Students write.] So come up with a design in order to achieve the lowest value of for terminal velocity, OK?”

Anna was actively involved with each group throughout the lab. She was in constant discussion with the students, and provided them confirmatory assurances all along they way. Anna also played the role of materials officer. She distributed one coffee filter to each group, and sometimes groups had to wait to receive a filter to start playing with it. When a group wanted a balance, she went and retrieved it from the front of the room. When a group wanted more filters she went and got them for the group. By managing the materials and steering questions, Anna was controlling the room, controlling the dialog, and controlling the pacing of the lesson. These methods are very effective classroom management techniques; they ensure the classroom is entirely managed by the teacher. However these methods are counter to encouraging engineering design divergence.

Anna also redirected the students towards easier methods such as in testing variables and analyzing graphs. As students thought through what they could change, Anna steered several groups towards varying the mass. One group was going to change the height of the coffee filter’s basket, which would change both mass and surface area, but Anna encouraged them to only associate that change with a changing mass. I think Anna thought students would see larger changes among their position-versus-time graphs if they varied the mass. Later, when Anna saw that finding endpoints on the terminal velocity duration was more difficult than estimating the slope of any part of the terminal velocity x-t graph line, she revised her recommendation and told groups to look for the slope, or the magnitude of the terminal velocity. Anna referenced how much easier it was to take the slope a total of seven times in class.

In summary, Anna reduced student choice by increasing comfort and support for the students. In this challenge, Anna was the sounding board, approver, and sometimes designer for her students. In planning, she seemed to approve of the challenge's scaffolding as a support for student sense-making, but in teaching she took responsibility for almost every decision away from the students. She became protective of them to the point that they would be shielded from all but the most easy opportunity for success when it came to seeing the right data emerge in the experiment. Although Anna started by not telling the students what to do, eventually she guided them in role selection, criterion selection, data analysis, and recommendations.

Anna steered students to do "easier" options throughout the lesson. Anna wasn't sabotaging the class (by telling them what to do she limited their opportunity for productive struggle and failure). Instead, Anna was trying to make sure students were set up for success, and that they wouldn't have to struggle with issues present in some "harder" options. But in providing the criterion that the students should use, Anna was not allowing students to prioritize criteria, which is a goal of the NGSS "define" bubble and is stated explicitly in Appendix I (NGSS Lead States, 2013c).

This lesson illustrated how Anna took on much of the responsibility of learning *for* her students. She made sure they would get the right conclusion by telling them what conclusion to make. This aligns with much of Anna's "regular" (non-engineering) physics and physics-inquiry instruction. Anna usually prepares one correct solution set, physically does labs for herself, thinks through possible student moves in labs thoroughly before students try, and is thrown when students invent ideas that she didn't anticipate. By Anna's own telling, her preparation routine was in support of making things easier for students.

Anna apparently believes struggling is not productive, and maybe even that struggle is a violation of trust between her students and herself. Instead of emphasizing how important struggle is in the design process, Anna removed the struggle and provided students with directions. Her perception of an unintended consequence ("they might think I let them down") moved her from an intended-risk zone into a consequence-avoidance zone where she provided students with directions.

As the model in Figure 4.6 illustrates, a move that perhaps eluded Anna is the transition back to engineering design from a zone of intended risk. She got stuck in a fear of unintended consequences instead of saying that risky feeling is intentional and good in this challenge. Anna layered on the support, working hard to satisfy the class, bringing them materials, critiquing their ideas, guiding their problem definition when they faltered, and helping them interpret their graphs. In doing so, she supported her students and showed her concern for them by trying to ensure they avoided frustration. However, she never got back to the engineering design methods zone, and students lost the opportunity to make choices or learn to value failure.

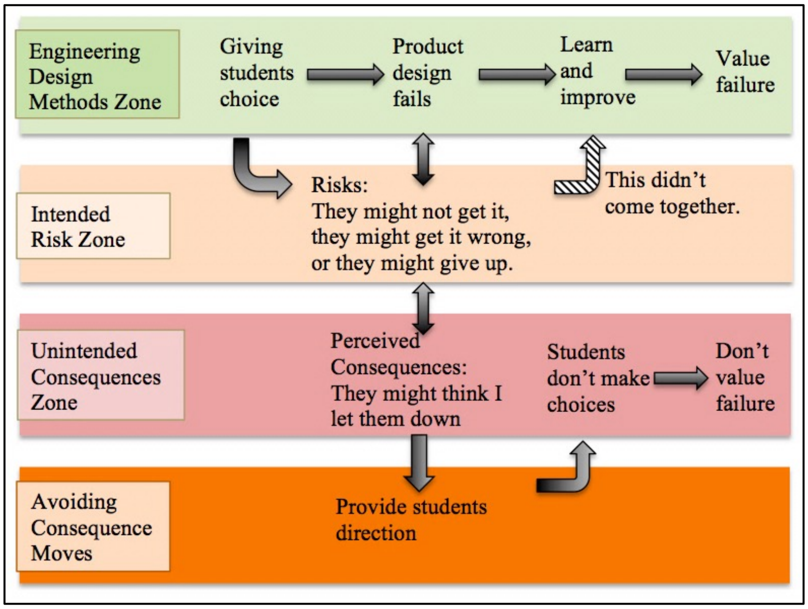


Figure 4.6 Anna's decisions model

In contrast, Leslie allowed divergent thinking in the Parachute Challenge, got students into the intended-risk zone, and let them use other resources like group reasoning and non-directive questioning to work their way out of it. Leslie was able to let go in the engineering challenges just as she was in her "regular" instruction. From the warm up activity to the selection of an optimal variable, Leslie expected students to design their own product and their own defense of that product. She loosely guided students by answering student questions with questions, and she didn't tell students the "answer" even when they tried over and over to extract an answer from her.

Leslie created opportunities for students to critique one another. In the “chunking” warm-up, Leslie required the students to debate each others answers on the board until class consensus was reached. Then, after Leslie introduced the challenge, she backed out of student conversations and just stood at the front of the room, watching and listening as students worked together to make meaning out of the first two pages of problem definition and design exploration without her direct input.

Leslie placed responsibility for lab skill expertise on the students, so she wouldn’t be the only one in the room who knew what to do. To explain the use of Logger Pro, she had one member of each group gather around one computer to receive a Logger Pro cheat sheet and to hear technical tricks like laying the ruler on the graph. But even when telling them a trick, she suggested they verify for themselves that it worked. She said, “You can see a little mini tick down here. Put—just take your ruler and put it here. Take your ruler and put it at the end of this line, and check it out yourself. Don’t take my word for it.” Armed with the new knowledge, each team’s representative then became the Logger Pro expert for his or her team instead of Leslie.

Leslie didn’t usually give straightforward answers to her students, and this continued in the parachute lesson. For example, in one group, “Jon,” “Van,” and “Jessie” were writing how they would measure the criterion they chose which was, the duration of time in terminal velocity. Leslie approached the group, and Van asked her how they would measure time in terminal velocity. Leslie did not answer directly. Instead, she led them through reasoning, including a meta moment about writing procedures, until they realized the method to use and understood the specificity with which they needed to write it down.

Leslie: Okay. So you're going to get a graph. How are you going to know how long the parachute was going at terminal velocity?

Katey field note: [Long pause. Just look at the students wait for her to answer herself! She waits them out.]

Van: [Inaudible]…look at the graph

Leslie: It creates a graph. It's not going to go, "Ding ding ding! [This is the terminal velocity duration!]"

Van: Well as soon as it flattens out, well not like flattens out, but like stops accelerating.

Leslie: Okay, what kind of pattern would that be?

Van: Linear

Leslie: Okay, so you're going to look for the linear section. See how I'm starting to describe exactly what I'm doing? What you're doing? That should be "How you're measuring the DV." You can add it in, you can add it. Then what are you going to do?

Van: [inaudible]

Leslie: Measure what? Why do, do you need that [pointing] or not?

Van: Well, no, we actually don't.

Leslie: Okay, so what do you think? [Long pause] Okay. [Pause] How are you going to calculate time from the graph?

Jessie: Time…stopwatch?

Leslie: Logger Pro doesn't—it's going to be like this [refers to the graphic on the page]. How did we find the time in here?

Van: We can just look at it.

Jon: We can just look at the graph.

Leslie: Well, velocity, this is position-time graph. [frustratedly picks up paper and points to top of back of warm up] What did we do to find the time that it was in [terminal velocity]?

Van: You wait 'til it becomes linear and then you look from there to the end.

Leslie: In what?

Van: [Inaudible]

Leslie: And we had it there. Okay. Okay. [Leslie walks away]

Van (to his group as he writes): Measure time from…v_t to v delta t. Measure time from v_t to end of graph.

In this dialogue, Leslie took time to explain the work to the student without taking away the authority of their ideas. It might have seemed obvious that she was looking for a specific answer, but students came around to reasoning and describing what they needed to describe to make sense of the phenomenon.

At lunch afterward, Leslie and I reflected on how her prediction that students could go through the design process alone was born out. Instead of stepping them through the process by recommending criteria, variables, or procedures, Leslie just cued them and let them go.

Katey: I also liked how you said, “We’re doing engineering design” as if they like, they’re like, “Oh that’s a thing.”

Leslie: “Oh engineering, got it!”

Katey: It was so, [snap] I mean that’s the quick transition. They knew exactly what to do, they totally, I think they totally got that paper this time, it was like, “oh yeah.”

Leslie: Yeah, I could say, “Fill out the first one and finish the page.” You know?

Leslie positioned students as classroom authorities. In Leslie’s classes, individual student accountability to each other and authority over their work as a norm settled in quickly and deeply so that in her engineering challenges, when she was most nervous about trying something new, it was completely natural to turn authority over to the students, which offered them the chance to make the challenge their own, increasing their buy-in and participation.

4.7.3.2 Discussion, Tension #3

The three teachers demonstrated various comfort levels with relinquishing responsibility for student achievement and failure in the Parachute Challenge. Not giving students the authority to work on their own meant the teachers restricted student divergent thinking and opportunities to learn to value failure. This means that too much scaffolding and reducing divergent thinking actually undermines learning about, and learning through, the engineering design process.

But allowing, or even scaffolding, failure is tricky in any classroom because "failure" is an awful word in most school contexts. Limiting opportunities for failure and substituting the teacher as the design authority instead of the student-designer undermines the authenticity of the engineering design task. To let students be the authority of their own work, the teacher has to release control and allow students to try strange ideas, maybe working against "correct" physics, and try ideas that the teacher knows will not yield clean results.

The three teachers' fears about wildly divergent student thinking in proposing design alternatives were mostly mitigated or managed with structures. Students in all the classes chose a wide variety of alterations to the coffee filters. They cut slits, taped multiple filters together, reoriented the filter, cut the cup shorter, and taped on paper clips. One group explored adding "jellyfish" strands to the basket. Anna did some leading by mentioning mass as something to change four times during problem introduction, and several of her groups ended up changing mass. Overall, however, all the students ran with their own ideas. Katniss insisted on the use of quantifiable design alternatives, but she turned a corner when she requested even wilder design contexts. Overall, this was not a stressful part of the activity though it had been a stressful part of planning.

4.7.4 Discussion of the Context of this Study

The results of this study are crucially dependent on the context of Merlin High School. The administrative climate at Merlin allowed these teachers to work under fewer constraints than most teachers face. It is noteworthy that these teachers did not face the pressure of standardized physics tests, and the Merlin administration team invited teachers to take risks and try new practices. This might have allowed these three teachers to focus less on specific content standards and to feel free to experiment and take risks in their instruction, including trying engineering design, when other teachers would not. Some teachers have to confront standardized tests and burdensome regulation even as they teach their basic subject matter, and those teachers might not be allowed, or feel confident enough, to try seemingly risky engineering curriculum.

Because of these factors, my results cannot be overly generalized to other teachers in every other context. However, it is worth looking at these three teachers' practices as a best-case scenario; you could expect to see tensions that arose at Merlin present in other settings too, plus more tensions, where the external pressure is more debilitating.

4.8 Epilogue

Over the school year the three teachers continued to work toward more and more authentic engineering instruction integrated with their physics classes. They planned and conducted a project to design an iPhone case, with two rounds of optimization.

Throughout the year, all three teachers continued to negotiate the three tensions described in this chapter. Related to Tension 1 (whether engineering design is added as a tack-on element of instruction or is integrated as the motivation for and context of learning new physics), all three teachers came to see engineering and content integration as the preferred method of doing engineering, although they still found it hard to do. Their iPhone Drop Challenge in February successfully created a need for students to learn about impulse and momentum conservation by studying force-versus-time graphs.

However, the teachers expressed regret that their Roller Coaster Building Challenge and Musical Instrument Challenge were not as content-heavy. Students only measured some physics quantities (velocity at two points, potential energy, kinetic energy, and efficiency) after the fact instead of designing with those quantities in mind as constraints. Connections between wavelength, frequency, and standing waves were missed when certain students just used trial-and-error to make the right sounds for their instruments in the Musical Instrument Challenge. They did not have to process, predict, or synthesize their data to understand waves; instead, they were given the correct relationships via lectures in parallel with designing the instruments.

The second tension (gathering enough data to make well-informed design decisions) persisted through the end of the school year. At times, the teachers struggled with what kind of data would be helpful for decision-making, and sometimes they struggled with whether various decisions were quantitative enough to feel appropriate for physics. In the Musical Instrument challenge, for instance, students were asked to build a musical instrument that could play eight unique pitches consistently. The teachers did not provide opportunities for students to test the frequencies during the design process, which meant that data on the most vital criteria was not incorporated into students' design decisions. None of the teachers seemed to feel this was a problem because this was how they had previously done the project although they were now calling it "engineering design."

A lack of iterations in the Roller Coaster Challenge frustrated Leslie in particular. The materials used, paper and tape, prevented iterations because the tape would tear the paper if parts were repositioned or removed from the coaster. Cutting and folding new parts was so labor-intensive that students could not easily sacrifice parts or start over. Leslie wanted her students to make their coasters and then improve them in multiple iterations based on measurements of physical performance from prior iterations, but she just did not have enough time.

The third tension (between classroom routines that supported students but limited student decisions-making agency) seemed to be reduced for all three teachers by the end of the year. Katniss's concern about students testing a quantifiable variable during the iPhone Drop Challenge was abandoned during the Musical Instrument Challenge. Her students attempted all manner of instruments, from a cigar box banjo to tonal, tin-can drums; and she let them try even when it was pretty obvious they would fail. She said "I don't know" much more frequently, encouraging students to test every question they had about materials or tools on their own, and even insisting on students' independence while learning how to use tools and cut wood using a miter box.

The teachers and I recognized something interesting that occurred among all the classes during the Musical Instrument Challenge: Anna's classes produced the widest variety and most ambitious projects by a long shot. In her classes were a full-size upright string bass, two working trombones, a bagpipe, hanging water-filled chimes, and electric and acoustic guitars. The other teachers also had water, string, woodwind, and percussion instruments, but many were exactly or closely similar to example projects the teachers showed: a metal-tube xylophone; water-filled glasses, bottles, or jars; rubber bands around boxes; and pan pipes. When we all recognized how far Anna's students had taken the project, we speculated that the wide range of divergent thinking might have been allowed by the support that Anna gave her students in class. This is in direct contrast to the tension in her first Parachute Challenge, where by protecting students from failure she limited student divergent thinking and risk. By the end of the year, Anna's students were widely diverging within the safe spaces she had created.

Leslie, Katniss, and Anna negotiated tensions individually and as a team over the year, and they were still learning and struggling all year long. Even though they each did four to five challenges in one year, and wanted to talk with other teachers about those experiences as PD leaders, they did not consider themselves comfortable or expert with engineering design at the end of the year. It seems that a year was not long enough for them to feel entirely at ease with engineering-design integration.

4.9 Conclusions and Future Directions

The teachers in this study worked together to attempt a new way of teaching in physics by integrating engineering design and science-content instruction. But during this work, three tensions were identified. (1) Separating physics content from engineering design came into tension with truly integrating engineering design into physics. (2) Time and technical constraints came into tension with adequate data collection for making design decisions. (3) Teachers' supportive classroom routines came into tension with students' divergent design thinking and agency.

The major conclusion of this work is that teaching moves that are productive for other classes at other times (like scaffolding instruction, providing emotionally safe spaces to learn, and teaching as efficiently as possible) might be unproductive in engineering-design instruction, as was seen in the Parachute Challenge. Even minor instructional issues like data collection techniques can impact engineering design implementation. When teachers' well-practiced routines, pedagogical moves, and instructive reflexes do not match their new expectation for engineering-design instruction, the teachers might choose to abandon the reform agenda, or pieces of it, and return to more solid, safer ground.

Even highly motivated, well-intentioned teachers might instruct engineering design in ways that are counterproductive to learning authentic engineering design. If providing structured support for learning efficiently (quickly) or for learning safely (preventing failure) restricts student's design experiences, then the more a teacher supports, the more the teacher limits the authenticity of the design experience.

Separating content-learning emphasis from design processes might make things easier, but that is not the intention of engineering design as integrated in NGSS and the *Framework*. Helping students collect and interpret a specific kind of data might seem easy for them to learn from, but it does not communicate the importance of, or skills to do, problem scoping and analysis in engineering design. And reducing student choice and divergent thinking might ensure they do not miss the point or ensure that they for sure see some “results,” but it undermines design mindsets and processes of engineering design.

Another conclusion is that even close-planning teams can have differing instructional implementations. All three tensions identified here point to the differences that occur when teachers actually teach in their own classrooms. In tension one, the teachers first identified their individual priorities and then compromised on them, but eventually taught their priorities their own ways. Each teacher handled this a little differently, which offers us a view of three possible ways to handle the tension but also implies that even when teachers have been involved in the same PD and the same planning, and have even reached a compromise together, they still could have different classroom outcomes.

4.9.1 Implications

All the teachers here had ambitious, best intentions. But they are human and have built-in means for self-preservation as well as a host of instructional experiences that guide their decisions. Here, we have seen that common and productive (for many purposes) decisions at times threatened authentic engineering design. This is a difficult tightrope for a teacher to walk. Curriculum developers should recognize that tensions between authentic engineering design and teachers’ usual practices might cause teachers distress or cause them to conduct engineering-design instruction in less than purely authentic ways.

Thus, this study has implications for science teachers, teacher educators, curriculum writers, and professional developers. Becoming aware of these three tensions may warn these people about potential pitfalls in engineering-design implementation and encourage conscientious monitoring of, and reflection on, these issues. Some of the more productive teacher moves for addressing these tensions, such as providing a warm-up to scaffold and model difficult data collection processes, and providing technical data sheets in the lab to reduce teacher-centeredness, could be employed in other classrooms. When teaching teachers what engineering design is, a teacher educator or professional developer could focus on and draw out these tensions to emphasize the importance of, and normalize feelings of risk around, authentic design experiences.

In addition to awareness of these specific tensions, the notion of tensions between teachers’ regular instructional practices and authentic engineering design opportunities in general might help teachers and professional developers analyze other difficulties around engineering-design implementation, constructively celebrating the good teaching practices used but seeing necessary adjustments to achieve the goals of authentic engineering-design integration.

Curriculum developers could use these and other tensions to specify specific actions to use, or mindsets to cultivate, in teacher plans. They will also need to be aware that efficient data collection could be a sticking point and can threaten engineering-design authenticity. Discussion of the data collection tension, tension 2, should help curriculum developers understand that even minor issues can have a major impact on the fidelity of the reform implementation.

4.9.2 Future Directions

Future work in this area could involve longitudinal analysis of the teachers' understanding of engineering and science over time. It would be interesting to follow this thread for all three teachers throughout the remainder of one, two, or several school years. My data set contains use of engineering design and teachers' reflections on engineering design for only one school year, and more data could be collected.

It could be productive to investigate how other science teachers respond to these tensions when they are integrating engineering design for the first time. The Merlin teachers' individual responses may or may not be similar to responses of other teachers across the sciences. Using the tensions identified here, researchers could extend this line of research to other subject science teachers trying to integrate engineering-design instruction, to seek a more expansive theory of integration prioritization.

Studying student outcomes after engineering-design instruction should be a priority of future research. In this study, student data was not collected, but in the future, research must explore whether the assumption of engineering design efficacy is correct or not.

To further assist teachers and students in learning engineering design, a clearer Nature of Engineering, a framework and representation of engineering useful for teachers, must be established and evaluated for clarity and efficacy. The ways that this study scaffolded engineering design and the nature of engineering design understandings should also be investigated and evaluated for authenticity and efficiency.

Chapter 5: Productive Resources for Engineering-Design Integration in High-School Physics

ABSTRACT

Recent reform efforts such as the NGSS to embed engineering-design instruction in K-12 science need to acknowledge that teachers will face tensions in reform implementation, particularly regarding science content, engineering design processes, classroom time, and teacher control. This study illuminates some "resources," or bits of reasoning, that teachers can draw upon to address these concerns and encourage engineering integration reform in high-school physics. This paper answers the question of how a physics teacher's existing resources help the teacher be productive in teaching engineering design in physics class.

This paper is part of a larger dissertation study on how high-school physics teachers take up the engineering instruction reform effort. The author collaborated with a team of three high-school physics teachers as a participant observer for one school year and used ethnographic methods to gather qualitative data from eight sections of general high-school physics.

This paper focuses on teacher "Leslie's" first day teaching engineering design, to see what got her past tension points that occurred. It examines how Leslie's resources, identified in her physics instruction, guided her teaching actions through moments of doubt in the engineering-design lesson. Some of Leslie's inquiry facilitation commitments and habits of mind, such as requiring student reasoning, not giving away steps or answers, requiring good data, giving up teacher authority, providing rich contexts, constructivist and social constructivist mindsets, and a growth model of learning, assisted her as productive resources in teaching her first engineering design challenge.

This study suggests that teachers who feel confused or overburdened with the engineering-design reform effort may be able to draw upon their existing resources to push through feelings of discomfort in (1) divergent (multi-directional) student thinking as required for engineering design, (2) content inclusion in engineering design, and (3) pacing. Resources related to open-inquiry facilitation specifically may be useful for other teachers integrating engineering design, too. Reform-implementation researchers, teacher educators, and engineering professional development providers should also acknowledge the role that resources can play in reform implementation and encourage teachers to find and call upon resources that they already have and that align with engineering-integration reform.

5.1 Introduction

Leslie heaved her lunch onto the table and dumped her body into a chair. Usually excited during the school day, today she was exhausted from teaching her first engineering design lesson, a self-planned engineering design challenge to build a catapult and learn about free fall. All the “mental work” she had been doing had drained her, and now she had just thirty minutes to eat, regroup, talk about the lesson, and get ready to do it again after lunch.

Leslie had started the year with no formal engineering experience, but she had been hungry for change and interested in integrating engineering design into her physics teaching. Leslie’s year was not without struggle. Like the lunch after her the first catapult class, there were moments when it seemed like engineering-design instruction might put in danger her goals for both physics learning and for learning the engineering-design process.

However, Leslie overcame tensions in instructional moments and stuck with engineering-design integration by drawing on her pool of resources (or bits of reasoning) and finding ways to productively combine those resources even when she felt confused, overwhelmed, or unsure. By the end of the year, after planning and teaching four engineering-design challenges, she was so enthusiastic about engineering design that she volunteered to facilitate an engineering-integrated teaching methods summer program, and then became a full-time STEM coach bringing engineering design to mathematics and science teachers across a whole county.

If teaching decisions can be viewed not as pure invention in the moment but instead as the outcome of influence from resources that the teacher already possesses, then this study sought to learn what resources, if any, Leslie called upon when she faced difficulties in integrating engineering design into physics, specifically into the Pumpkin Chunkin' Challenge. I found that Leslie activated some resources in both engineering-design instruction and inquiry-style facilitation in physics. If we want teachers to do engineering design in their physics classes, perhaps it would be useful to encourage teachers to find and examine resources that they find productive in other student-centered instruction, such as inquiry instruction, and draw upon these resources in engineering-design implementation.

This chapter sets the stage for the discussion of resources by, first, reviewing some traditions of engineering design and engineering-design instruction in higher education, before discussing how engineering and engineering design are envisioned in K-12 and specifically in high-school physics instruction. Next, this chapter describes the framework of resources used to analyze Leslie's instruction. Second, some of Leslie's resources in physics are identified to better describe Leslie and to point out resources that she possessed which were useful for engineering-design instruction. The list here is not complete and it is not even all the resources that I identified; it has been edited for space and pertinence to engineering design. Leslie, like everyone else, has myriad additional resources that she calls upon all the time. Third, this chapter explains ways in which Leslie's various resources were helpful during the instruction of her Pumpkin Chunkin' engineering-design challenge, especially during moments when these resources helped her overcome tensions she felt.

5.2 Literature Review and Conceptual Framework

Literature pertinent to doing engineering in K-12 as envisioned in the NGSS necessarily starts with how engineering design and engineering-design instruction look in industry, in higher education, and in K-12 recommendations. The traditional relationship of content to design in higher education stands in sharp contrast to modern recommendations for engineering integration. In higher education, learning the engineering process (engineering design) is held separate from engineering content (a.k.a. engineering sciences or the disciplinary knowledge needed to solve problems, the science of stress, strain, circuits, aerodynamics, etc.). In recent K-12 science reforms, however, the engineering processes (engineering design) are intended to be a vehicle for learning engineering concurrently with scientific content, not separated from that content. This literature review explores the causes and the outcomes of this shift, especially as it pertains to physics teachers.

Using the processes of engineering to teach science and engineering content may remind the reader of how the inquiry-instruction reform agenda proposed that processes of science (termed “scientific inquiry”) could be used to teach science content in the National Science Education Standards (NSES) (National Research Council, 1996). That was itself a major turn away from teaching scientific content (laws, theories, equations, models, and “facts”) separately from scientific processes (a.k.a. “the scientific method”). If indeed teaching science through engineering processes may be compared to the inquiry reform movement, then perhaps we should expect similar issues to arise during implementation. The second half of this literature review thus explores the problems in inquiry integration as a possible road map to problems in engineering integration, and then discusses literature on engineering integration with an eye for integration problems.

5.2.1 Engineering Design is a Complex Process

Before any reform or integration can occur, K-12 science educators will have to try to understand what engineering design is. Although engineering design is an amorphous and “elusive creature” (Dym et al., 2005, p. 103), it is critical to doing and learning engineering (Grinter, 1955), so having a definition to translate to instruction is a good starting point. Evans, McNeil and Beakley (1990) said engineering design is “a systematic, intelligent process in which designers generate, evaluate and specify concepts for devices, systems, or processes [to] achieve clients’ objectives [while] satisfying a specified set of constraints.” Engineering design has certain components, such as analysis, constraints, modeling, optimization, and systems (Katehi et al., 2009), and it requires certain mindsets, such as embracing multiple possible solutions (Katehi et al., 2009) and the utility of productive failure, alternating and iterating solutions through divergent and convergent thinking (Radaideh et al., 2013), and careful monitoring of progress towards goals and subgoals.

Traditionally, students in higher education learn engineering design separately from engineering sciences (like fluid dynamics, or electrostatics), which make up the bulk of engineering coursework (ABET, 2013; Grinter, 1955). In contrast, the NGSS emphasized how engineering-design practices and science content should be learned concurrently; “An understanding of engineering [design] practices can develop as they are used in the classroom to help students acquire and apply science knowledge” (National Research Council (U.S.), 2012, p. 201). This was a major shift away from the traditional separation of engineering-design instruction from science instruction.

K-12 descriptions of engineering are tightly aligned with many aspects of the scope of engineering found in classical descriptions, including problem solving and the creative and collaborative nature of the engineering profession (Brophy et al., 2008; Grinter, 1955; Truesdell, 2014). But Truesdell’s (2014) K-12 definition misses a component of engineering design that both Grinter and NGSS recognize, the contribution of social and cultural goals and assets.

Because defining engineering design is hard, models have been suggested to guide engineering learning and practice. It should be no surprise that just as defining engineering design is hard, a complete and agreed upon model of engineering design is also hard to pin down. Also, of course, models are limited because they necessarily simplify the complexity and intricacy of engineering design to a more usable, but less nuanced version of the modeled phenomenon.

The NGSS (NGSS Lead States, 2013) provided two models of engineering design: one is a list of eight science and engineering practices, and the other is a diagram depicting a bi-directional cycle of defining the problem, developing solutions, and optimizing the solution. These two models represent an unresolved mismatch or conflict between two "visions" of engineering design in the NGSS. A teacher looking around for help to resolve this conflict will find it does not get any clearer, because there are many other models for engineering in K-12. For a non-engineering-trained teacher, this abundance may cause confusion about what engineering includes and what engineering learning should teach.

This author contributed to a model for high-school use that helps to clarify the "elusive" process. The model includes four phases of engineering design—two divergent phases, problem definition and design exploration, and two convergent phases, design optimization and design communication—in a cycling, iterative, inter-informing schema (represented by overlapping circles) (Johnson et al., 2015). This model, shown in Figure 5.1, is similar to another four-stage model—problem definition or framing, conceptual design, preliminary and detailed design and build, and design communication (Radaideh et al., 2013), which itself took a "five-stage prescriptive model of the design process" (Dym et al., 2005) and merged the third and fourth stages.

The four-phase model shown in Figure 5.1 became important to this dissertation because it was the model that teacher Leslie internalized, discussed at length, compared lessons to, and built lessons around, including her Parachute Challenge discussed in this chapter. This model also complies with the NGSS model and tries to operationalize the NGSS practices of science and engineering for classroom use.

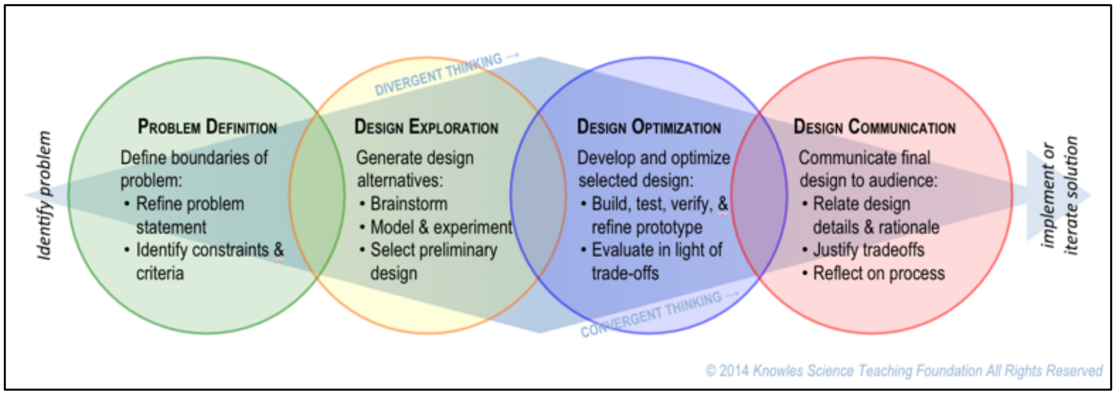


Figure 5.1 [also figure 2.4]. The KSTF Four-Phase Engineering Design Process Model (Johnson et al., 2015, p. 19).

The NGSS also includes engineering standards, but these all focus on engineering design, not engineering sciences. For instance, the high-school engineering and technical sciences disciplinary core ideas (the standards) are defining and delimiting engineering problems, developing possible solutions, and optimizing the design solution.

While the NGSS provides models and standards, the NGSS is not instructive of curriculum or pedagogy; it does not provide daily objectives, lesson plans, or concrete pedagogical practices. It only provides the endpoints or standards for what students should learn, not what teachers should do. For recommendations on how to teach engineering in K-12, one must look elsewhere.

5.2.2 Recommendations for K-12 Engineering Pedagogy

Because engineering as part of science has little history in K-12 education, some recent curricula, specialty PD offerings, and books have made recommendations for how to teach engineering in K-12 classrooms. Some recommendations treat engineering as a stand-alone curriculum, such as in *Engineering is Elementary* or Project Lead the Way (PLTW), and some recommendations focus on engineering as an integrated part of STEM in science and or mathematics. This section draws mostly from three sources that do not differentiate between recommendations for stand-alone versus integrated engineering instruction.

Douglas, Iversen, and Kalyandurg (2004) claimed that students should use the engineering design process to learn science and engineering standards, and that teachers should emphasize interdisciplinary, real-world applications and contexts of science. Douglas et al., (2004) and Truesdell (2014) suggested using rubrics, peer critique, having students restate the problem in their own words; using work logs; assigning small, daily assessments; emphasizing sketching; and creating role models, mentors, and partnerships.

Some recommendations seem like oversimplifications of engineering design. These include using an informative design brief or client letter that requires basic reading comprehension, not engineering analysis (Katehi et al., 2009, p. 84); setting up artificial roles and needs (the teacher as client, the student as engineer) instead of utilizing real-world challenges; setting arbitrary design constraints through materials lists, not through thoughtful problem scoping; and actually building designs only a few times in a year of science class or only when the designs are very simple (Truesdell, 2014). Some recommendations may be necessary at first or for some populations or ages, but these recommendations do not encompass what engineering is, such as teaching the “rule of brainstorming,” quantity of ideas over quality of ideas (Truesdell, 2014, p. 31).

In the ASCD’s practical recommendations for K-12 engineering-design instruction, Truesdell (2014) exhibited a bias against student choice in a few of her recommendations. She recommended that the teachers should set up the entire project for the students, providing them all the constraints and criteria they would need instead of allowing them to determine the specific problem they would solve. She reported that she herself has been hesitant to opening up material options to student choice and “allow[ing] teams to use whatever they want” (p. 34), and she reported consciously holding some variables constant across all the teams, thus limiting student choice in scientific inquiry practices during engineering-design instruction.

All of these recommendations demonstrate the limitations of K-12 engineering pedagogy. That is, reformers have not quite figured out how to advise teachers unfamiliar with engineering on how to teach engineering design in the K-12 classroom. “As yet there is no clear description of the knowledge and skills needed to teaching engineering to children” (Katehi et al., 2009, p. 103).

Research shows that implementing teachers must grapple with just what engineering design is, and will struggle with the mathematics, science, and open-endedness of engineering instruction as they learn in PD (Katehi et al., 2009). Other expected issues in integration include teacher deficit thinking about how their students would handle engineering design, and negative impressions of their own ability to negotiate the complexity and demands of engineering-design instruction within limited available time and resources (Douglas et al., 2004). Additional research is required, especially observational research of teaching and professional development, because most of the research on K-12 engineering teaching so far comes from examining curriculum for classrooms and PD, not from watching actual instruction (Katehi et al., 2009).

5.2.3 Research on Engineering in High-School Physics

Given engineering's lack of history in K-12 education, and given the specialization of engineering education preparation, it is no wonder that few teachers feel prepared to teach engineering design (Banilower et al., 2013). Physics might seem like an obvious engineering-design integration site because engineering and physics seem so closely related (Dare et al., 2014) and physics teachers report taking more engineering coursework than other high-school science teachers, 28% to 10% respectively (Banilower, 2013, p. 5). However, taking one or two courses in engineering would not make a physics teacher knowledgeable in engineering design or engineering-design instruction, and engineering-design courses are the minority even in engineering-track majors. (No data is available on the type of engineering courses taken by high-school physics teachers.) Even the 28% that took at least one engineering class in higher education might find the NGSS's combination of engineering sciences (i.e., learning physics content) and engineering design to be a strange interpretation of teaching engineering.

Research on engineering integration in high-school physics is slim and based largely on self-reporting of use and outcomes instead of observation and student evaluation (i.e., tests) (Dare et al., 2014; Katehi et al., 2009). Dare et al. conducted an observational study of nine high-school physics science teachers teaching 31 physics and engineering lessons after an intensive engineering design PD on "physics + engineering" integration for physical science teachers (teaching physics and/or chemistry). The teachers in the study taught their students a "physics + engineering" lesson that they were led through in a four-day PD on engineering in the physical sciences. The PD organizers stressed the importance of explicitly linking engineering design and physics in engineering design challenges in the classroom. However, the authors found that physics teachers doing "engineering design" lessons in their classrooms favored soft skills of engineering (especially collaboration and creativity) and student enjoyment outcomes over maintaining a focus on physics content. Sometimes the physics content was only present in problems in the back of a laboratory handout packet accompanying the activity. In those cases where students mostly used trial-and-error or tinkering, the authors evaluated students' engineering design actions as only "engineering-like" (i.e., not robust, authentic engineering). In cases where students engaged in "variable testing," the authors found that the teachers connected variable testing to practicing experimental design but not to physics content. The authors called for researchers to elicit teacher beliefs about engineering before a PD, to foster discussion about what engineering integration would look like before instruction began, and to model the creation of instructional goals and units that include physics and engineering content.

5.2.4 Inquiry Instruction and Engineering Design

Inquiry instruction is an active learning process in which students construct understandings of physical phenomenon through investigating research questions and data analysis (National Research Council, 2000). The NGSS continued advocating for the practices of scientific inquiry but backed off from the theme of learning by doing that was present in the NSES. Inquiry instruction as recommended by the NSES is related to scientific inquiry, or what scientists do, because it involves students designing and conducting investigations into scientific phenomena to learn the science content instead of being taught content didactically. More student-led inquiry instruction is called "open inquiry" (Bell et al., 2005; Rezba et al., 1998).

Open inquiry instruction may seem naturally aligned with the NGSS vision of engineering design to teach content because both require students to learn by designing an experiment or a product. However, little research acknowledges the connection, and the exploration of engineering design as related to self-guided inquiry is an area still in need of research. "A more systematic linkage between engineering design and scientific inquiry to improve learning in both domains has intriguing possibilities" (Katehi et al., 2009, p. 157).

The teachers in this dissertation study used inquiry instruction within their engineering-design instruction. Although this is essentially an observational finding of this study, it is necessary to highlight engineering design's potential relationship to inquiry here. Integrated engineering-design instruction, in which instructive inquiry practices (students posing questions, developing and conducting a controlled empirical tests, then reasoning, forming, and justifying explanations from evidence) are essential to the design process, needs to be distinguished from other forms of engineering and engineering-design instruction. More typical engineering-instruction methods are (1) using engineering as a culminating activity to apply learned science concepts (Roehrig & Moore J., 2012); (2) using engineering design in a context that typically can be solved by tinkering, not by science content (Dare et al., 2014; Katehi et al., 2009; Roehrig & Moore J., 2012); (3) engineering instruction devoid of experiment, where testing is not systematic and tinkering or trial-and-error is allowed to suffice in solving the problem (as was also found in Dare); and (4) teaching engineering concepts (instead of science or mathematics content) like, for example, learning how to specify criteria and constraints (NGSS Lead States, 2013d, p. 291). So, although a linkage between engineering-design instruction and inquiry instruction seems promising, much remains to be investigated, articulated, and analyzed regarding this conceptual relationship.

5.2.5 Potential Engineering Design-Integrated Pedagogy

So what could engineering integration look like in a high-school physics instruction? More specifically, what should engineering integration look like if implementation mirrors NGSS and *Framework* recommendations, and what could it look like given the current state of available curricular materials, teacher preparation, and constraints on classroom time?

Assuming that the NGSS describes a viable and authentic version of engineering design, and that the enactment of NGSS will follow NGSS and *Framework* recommendations to use engineering design to teach content physics as well as engineering, then engineering-design instruction should be content-inclusive, i.e., should try to teach content within the activity (C. M. Cunningham, Knight, Carlsen, & Kelly, 2007; National Research Council (U.S.), 2012; NGSS Lead States, 2013d). Also, the teacher must follow many other best practices: remain student-centered, responsive, and data-oriented; demand claim-evidence-reasoning logic; use inquiry instruction; promote positive group norms; and support equity and respect in the classroom. A hypothetical vignette is included in Appendix 5.6 to provide the reader with some sense of how engineering integration might look in a high-school physics classroom, with the caveat that classrooms are extremely complex and it would not be possible to write down every detail of a class's instruction in a handful of pages.

But classroom realities, available curriculum, and current teacher preparation might mean that integration of engineering design into high-school physics would actually occur differently than the integrated, design-into-content vision described above. Engineering instruction can sometimes be chaotic or unorganized (Dare et al., 2014), and teachers may sometimes feel uncomfortable (Katehi et al., 2009; Truesdell, 2014). Consequently, instead of doing the whole design cycle, including analysis, constraints, modeling, optimization, and trade-offs (Katehi et al., 2009), teachers might focus only on variable testing without indicating how specific variable testing relates to improving a design (Dare et al., 2014). Engineering design processes may digress to following discrete steps (Dare et al., 2014; Holstein & Keene, 2013) or to trial-and-error (Dare et al., 2014). Teachers might focus on student enjoyment and "hands-on" engagement (Dare et al., 2014; Katehi et al., 2009) instead of exploration, analysis, or interpretation (Holstein & Keene, 2013).

If commercial curriculum and engineering materials are selected to help in the implementation, they should be chosen to fit the school or teacher's ideals for the amount of inquiry or discovery learning involved. Many commercially available curriculum materials, such as the popular PLTW series, are intended to be their own, stand-alone courses, outside of science class. While that does not mean they would not be useful in science class, it reduces their utility as off-the-shelf curriculum.

"Most" of the curricular materials reviewed by Katehi et al. (2009) only offer "encyclopedia-like" explanations of science (natural world) content that are then reinforced in laboratory activities (p. 80), limiting the inquiry experience for students; but others provide more opportunities. Some, including PLTW's middle school "Gateway to Technology" and the Society of Automotive Engineers' high school-level course, "A World in Motion," use scientific inquiry to demonstrate or discover laws of nature. For instance, "A World in Motion" has students investigate gear ratios to help design a toy car's speed and torque.

No matter what materials are selected, developed, or reformed, teachers, in order to maintain curriculum fidelity, will need subject-matter knowledge and appropriate beliefs about teaching, about students, and about curricular materials (Holstein & Keene, 2013), including a basic understanding of engineering concepts (Katehi et al., 2009).

5.2.6 Resources Framework

This dissertation analysis rests on a "resources" framework. No matter what curricular materials are selected, developed or reformed, teachers' knowledge and reasoning "resources" will be involved in their decision-making as they plan and teach engineering design. The resources framework states that resources are bits of knowledge and reasoning; these involve skills, mindsets, attitudes, and teaching practices that a teacher may call upon in moments of teaching decisions. Resources can be views about student learning and how students learn, views about pedagogy, classroom routines, and other bits of knowledge and reasoning that are activated based on context. For some authors, resources have a finer grain size than beliefs and are sometimes described as analogous to diSessa's p-prims (Louca et al., 2004), but for this study I am simply identifying various views, habits of mind, and patterns of action that seem tethered to decisions in various contexts. My conceptual framework states that (1) teachers have repertoires of resources that are larger than what you would see used at any given time; (2) resources get "called up" or activated in various combinations due to situational conditions in response to classroom, contextual, peer or social contexts, and are not necessarily consistently called up every time; and (3) sometimes co-activated resources can be highly unstable, and sometimes they can be mutually reinforcing.

This dissertation analysis also uses resources more broadly than either Hammer (2000) or Hammer and Elby (Elby & Hammer, 2010). Here the term is used to categorize locally coherent patterns of thought and action that were seen repeatedly throughout the year across instruction, planning sessions, and interviews. Some of these patterns are productive in that they seemed to explain how teacher Leslie ended up successfully adopting engineering design into her instruction. The resources framework provides an intuitive sense that certain bits of reasoning are drawn upon to influence teaching decisions while trying to bring engineering design into the classroom. Within the resources framework, sense-making and in-the-moment decisions are guided by the combining of these resources, and this chapter tries to identify some resources that seem especially productive in engineering design. Acknowledging and investigating resources may be helpful for understanding the thinking and deciding that a teacher does.

This chapter focuses on teacher moves, authority, what counts as knowledge and learning in physics or engineering, and whether that knowledge is fabricated by the learner or transmitted by the teacher. These resources can come together to inform decisions regarding pedagogy, curriculum, instructional guidance, etc., based on the moments and activities surrounding each decision. However, resources are not always consistently activated. A single human's actions may seem to reveal internally conflicting “beliefs,” perhaps because resources are just surfacing differently moment-to-moment or situation-to-situation. Significantly, by seeking and documenting productive resources, this study intentionally seeks assets that Leslie brings to the new teaching situation, instead of engaging in the more common practice of seeking her deficits and misconceptions in order to ward off certain behaviors or decisions. Perhaps the assets-based framework used here will inform teacher PD in a more effective way than typical deficits-based or misconceptions-based frameworks do.

This chapter focuses on Leslie’s first attempt at integrating engineering design because that is when she wrestled with the adoption the most and, therefore, it is most informative about instructional problems that might arise for other teachers. However, even though this chapter discusses events from early in the school year, data from later in the year contributed to identifying the resources that were helpful in early adoption.

5.3 Methods and Data Analysis

In 2015, physics teacher Leslie and two of her colleagues invited the author to help them integrate engineering design into their physics classes in the 2015-2016 school year. This chapter focuses on Leslie’s first attempt at engineering-design planning and instruction. Leslie got her B.S. in physics and her Masters in science teaching and then taught physics for six years before the study began, three of them at the study’s site, Merlin High School, a 2000-student “urban suburban” high school near a Central East Coast city.

I observed 45 of Leslie’s on-grade-level physics classes (for which the mathematics co-requisite was algebra 1) for about 67 hours in the 2015-2016 school year. I used ethnographic-like methods as a participant observer (including passive classroom observation, field notes, active classroom interactions, active planning, analytic memos, and teacher interviews) to become immersed in Leslie’s physics teaching team as a moderate participant, maintaining a “balance” between participation and observation without taking on the full activities of the teachers (Spradley, 1980).

Although ethnographic methods were used, this study was not primarily focused on understanding the culture of the physics teachers or their classroom cultures, as is the traditional intention of ethnographic research (Preissle & LeCompte, 1993). Instead, ethnographic techniques were used to generate rich descriptions of the teacher’s behaviors, to “catch the diversity, variability, individuality, uniqueness, and spontaneity of social interaction” (Cohen, Manion, & Morrison, 2000, p. 139) in the high-school physics instruction at Merlin.

The study began with descriptive observations that were documented by taking continuous field notes throughout the class period and collecting audio and video recordings. The recordings and documentation included lunchtime conversations, planning conversations, on-line conversations, emails, and teaching documents. The author began with an intuitive sense of what could help people teach engineering from two previous pilot studies; from literature; and from experience teaching physics, engineering projects, and sculpture classes.

Over time, the study's data collection and data analysis became intertwined. During early physics observation in October, before Leslie began trying to integrate engineering, I began noting as a list of rationale for actions (X is a reason for doing Y), means-end (X as a way to do Y), and functional (X is used for Y) domains (Spradley, 1980). Tags were used in the field notes to indicate influencing resources (bits of reasoning) such as "foundations of science," "growth mindset," "bigger pictures," "creativity," and "student decides" (see Appendix 5.1 for my complete list of tags).

I began to identify some resources, patterns of actions or thoughts, as "productive" or seemingly activated and helpful in various moments and chased them in my data collection and analysis. After identifying a potentially productive resource, I sought it in more data sources. In focused observations of engineering design planning and instruction, and during engineering instruction observation, I remained alerted to the same resources and kept notes of when they appeared. If a pattern began to emerge, I noted that and asked about it, sometimes directly and sometimes indirectly. I made further selective observations of Leslie toward the end of the school year, observing her class more than the other teachers combined in June. My research progressed and I wrote analytic memos to help myself understand the breadth of data and phenomena to include in my analysis. I discussed my emerging ideas with my research group and decided to discuss Leslie in positive terms as opposed to deficit terms, and to not include contrasts with other subjects. Then I returned to a time, the first day in the Pumpkin Chunkin' Challenge, when Leslie struggled in engineering-design instruction but persevered, as a specific instance of her resources functioning productively. Leslie chose to try to plan an engineering design lesson first because she wound up several days ahead of her team before the Thanksgiving break. This chapter focuses on that effort.

5.3.1 Why Leslie and Why This Day?

Leslie was the first of the three teachers in her planning group to try engineering design. Striking out on her own when she had a few extra days before Thanksgiving, she and I planned the lesson, and both she and her colleague Anna taught it. At lunchtime, after observing Leslie's first attempt, I was excited and eager to debrief her, but she was exhausted and needed some minutes to get herself together. This was very irregular behavior for her, but she said the "mental work" of teaching that design challenge had exhausted her. Of all the potential stories that could be told about teaching engineering design, I was drawn repeatedly to Leslie's first try and that "mental work" that she reported. Telling the story of that mental work in terms of resources is the content of this chapter.

After watching all three teachers plan and instruct the Parachute Challenge in December, I realized how significant an achievement it was for Leslie to get past that first Pumpkin Chunkin' Challenge (another teacher had simply abandoned her first engineering lesson when she became uncomfortable), and with Leslie's reflection confirming that it was significant to her as well, I returned to the planning, the interviews, and other conversations about this lesson to understand how Leslie dealt with the stresses she while teaching it.

Reviewing Leslie's first try again—and with the comparative observations of the other teacher's engineering design attempts during which one teacher abandoned the challenge due to stress, and two lessons in which the teachers used heavy scaffolding to assist the students to success (see Chapter 4)—I realized that Leslie was doing less "teaching" in the moments that caused other teachers distress. When teachers Anna and Katniss were distressed they tended to give additional directives and instructions, but Leslie did not. She was able to retain the most student sense-making and student decision-making, which I valued as closest to the inquiry-type engineering that the NGSS describes. Why could she do that?

I reviewed my field notes of the Pumpkin Chunkin' Challenge and completely transcribed Leslie's 5th period and 6th period classes as well as our lunchtime conversation after 5th period. While transcribing, I was reminded what things made her most uneasy, and what teacher moves she made to get past or around them. Some moves were typical of Leslie, such as encouraging student decisions, not giving away answers, and relying on good lab practices to keep students moving. Connecting her practices to instruction that allowed students to design independently, I had a breakthrough realization that inquiry instruction seemed to fit well in engineering, too, and in ways I had not expected (see audio memo transcript Appendix 5.3). The resources that surfaced during Leslie's successful open-inquiry facilitation appeared again as assistive resources during difficult or confusing moments of engineering-design instruction. It was not always easy for her, but she was able to provide a student-driven engineering design experience. This pattern also held for Leslie through two more engineering design challenges.

After the last day of school, I conducted a member check (a direct check-in with a study's participant about that study's conclusions) with Leslie in which I ran my ideas past her for her input. Months later, as I wrote this chapter, I conducted a second member check with her and each of the other teachers individually and received their support for my conclusions.

Dare et al. (2014) asked for research on a teacher with a physics degree doing engineering integration, and Leslie fit the bill. However, I also chose to focus on Leslie's resources because something spurred her to be first to try the Pumpkin Chunkin' Challenge, and something spurred her to stick with it even though another teacher balked at the difficulty of doing it. This chapter analyzes what kept Leslie in it and shares the idea of productive resources for engineering-design instruction so others may learn from her example. She was not a super hero; she just drew on some resources that worked in that situation.

5.3.2 Positionality Statement

I walked a line between teacher-collaborator and engineering integration expert as I observed and worked with Leslie. I have no doubt that my observations and analysis were influenced at least in part by my experiences teaching, observing and evaluating student teachers for several years. It is likely that the various teaching moments that I responded to in this study aligned with my sense of "good" inquiry-oriented, student-centered teaching. Additionally, I have studied both physics and sculpture and believe that making things involves learning just as I think teaching involves learning, too. Exploring similar constructivist epistemological stances in myself probably influenced my interest in engineering and certainly my interest in Leslie.

5.4 Productive Resources in Leslie's Physics Instruction

Like all teachers, Leslie had a pool of many resources that she drew upon at various times during instruction. Some of her physics instruction resources helped her the first time she tried engineering-design instruction, particularly those related to inquiry facilitation in physics. To begin this analysis, this section describes a non-engineering inquiry lesson in Leslie's classroom and then discusses the resources that were identified while watching her teach.

5.4.1 A Vignette of Leslie's Non-Engineering Inquiry Instruction

This section describes how Leslie taught a level 2+ inquiry lab on pendulum length versus period. She did not provide procedures, like you might in a level 2, but she did give some directions for how to gather ("take a wide range") and process ("graph period on the x-axis") data to get her students to a place where she was sure they could make sense—seeing a parabola vertically positioned around the y-axis. So it was not quite level 3, but it was more than level 2, hence, 2+. This episode is being described because it was tagged “inquiry with ease” in the field notes.

It was the last class period before back-to-school night and Leslie’s room was sleepy and warm. Leslie’s 6th-period class of seniors and juniors came in from lunch at the end of the 10th day of class, on an 85-degree day. Some students slumped down into their chairs before they even noticed the bowling ball hanging from a 2-meter cord at the front of the room. The ball was covered in yellow caution tape, and a stool was supporting it so that the cord was just barely slack.

No one mentioned the bowling ball as the class brainstormed examples of pendulum and Leslie wrote them on the board, such as a metronome (inverted pendulum!), a wrecking ball, a swing, and a pirate ship at the theme park (a boat-shaped bob!). Leslie recalled with the students that they had previously examined whether mass affected period and had discovered it did not. The pattern they found was a flat line and the equation was y (period of pendulum) equals a constant. Flat lines being pretty boring, Leslie said, “Waa-wahhh!” like a sad trombone.

“Today,” she told them, “we’re going to examine another variable.” The students brainstormed possible variables, and she revealed that they would not be testing angle of release. Even though many students had previously designed experiments in which the angle of release was held constant, she revealed now that the angle of release did not affect the period, to which one student dropped his chin to his chest in a gesture of frustration.

“This time,” she said, “we’ll investigate length of the pendulum. And to get us amped up, I have a video.” A thumping electronic beat played over a video of swinging black-lit masses all with different lengths. Leslie jokingly played up the mood of the video, “Whoooooaaaa!!!! Who-o-o-a-aa!!!” she said, as the bobs seemed to merge and separate on cue like a ballet.

She told the students to design an experiment to figure out how the length of a pendulum relates to its period and to be prepared to predict the period of her mystery pendulum, the bowling ball. She set them off with only a few more pieces of advice: “Test as wide a range as you can and graph time on the x-axis,” even though the dependent variable would usually go on the y-axis. “I believe in you, go!”

After the students started writing their procedures, one of them approached Leslie and asked her to clarify her statement about angle of release not affecting the period, to which Leslie said, “Go test it, don’t take my word for it!” When that student went back to his group, they did test it, and after testing six angles decided that, indeed, the angle did not matter enough to bother with, but also decided that in their length test they would keep it constant just in case they had not measured it well and it did matter some.

The students wrote in their groups until she approved their procedures. Leslie rarely rejected these; she usually just offered critique, often restating her previous advice about testing a wide range including very short lengths. She told one group, “[the increments] don’t have to be even.” Even while letting the exact procedure emerge (how many swings to time, where to start it, what mass to use, etc.), she could have said, “Start at 10 centimeters, and make increments out to 1.5 meters,” but she did not. She just continually said, “Use a wide range of lengths,” knowing that they would need a wide range to see the quadratic pattern well. After ten minutes, all the groups had started to collect data, except one group that was still arguing about how to best time the pendulum period based on their experiences in the last lab.

Eventually, all groups were taking data. Leslie eyed them from the front of the room, listening. Some of the test stands were rocking and wobbling creating compound pendula, and I was concerned by how much energy could be lost if a group was say, measuring ten swings, so I asked Leslie what she thought. We had a little discussion about how we did not really know how damping would affect the period, but we thought it probably only affected amplitude, which no one was measuring.

However, something else fishy did catch Leslie’s eye, and she headed over to a lab table, under the guise of sorting the some resistors and wires along the back wall of the classroom. While sorting, Leslie asked the timing teammate about error, and he said his group reasoned that he might be as much as a tenth of a second off on each click. “Okay, so how much off per trial?” Leslie asked. Maybe 0.2 seconds. Leslie, knowing that they were measuring more than one swing per trial, then asked, “So how can we reduce the effect of that error?” Sure enough, the student said they were measuring the total time for four periods to reduce the effect. So she had seen it right, they were measuring four trials, and yet, what were they recording?

“Then what?” Leslie asked. She was driving at something without saying explicitly what her concern was. The student explained how he would take the average of the numbers recorded; “Then add them all up and divide by the number you have.” He was missing the obvious piece; to make a period-versus-time graph, Leslie wanted the period of one swing, not four. But Leslie, instead of telling him what to do or telling him her concern straight out, stuck with her questions. “So you have times of four periods, now you have the average time of four periods, how do I get the average time of one?” The student paused for a blink and then it worked. “You divide by four,” he said. “Yah!” she said. And with that Leslie went back to sorting by turning away. It is possible that previous lab this group had not divided by four, and Leslie did not know if they had or had not. It would not have mattered either way for finding the graphic pattern between mass and period; the period was not changing and so the relationship of mass to one period or four periods would have been the same either way—no change. But this time, Leslie wanted all the students to be able to predict what the mystery pendulum’s period was. If the group’s calculations, graphs, linearized graphs, and eventual equations were off by a factor of four or four squared, then their prediction would also be off by a factor of four. Leslie made sure that did not happen, not by charging over and saying, you need to divide by four, but by casually asking them what else they were going to do to get the period of just one swing.

Leslie did not redirect any other groups’ work throughout the rest of the lab. The lab paper prompted graphing and sense making by asking for narrative relationships once the graph was made. Leslie praised the graphs, and listened to debates between students arguing for various best-fit lines. When she felt one student was pushing too hard for a linear pattern, she told her, “This is such a beautiful *curve*, but it’s just going this way. You are trying to force it.” She did not offer an alternative or a way out. She did, however, offer several students large erasers, saying, “Do you want a big eraser? They’re always right here for you.” Offering erasers was a subtle hint that revisions to best-fit lines were acceptable and even expected.

The classroom felt very comfortable to me now in the last thirty minutes. Students were graphing. Leslie walked around, almost always with something else in her hands, like a Trolls pen, or a slinky, or a tea mug. Fiddling with the trinket, she stood and listened to the students talk to each other. My field notes said, “She does a lot of standing at groups, and often they ask her questions without her prompting it. She’s just there, and they can use the help or not.” For instance, one group was debating whether their curve should go through (0,0) on their graphs. Finally they asked Leslie for help. She replied calmly and flatly, “Does that make sense in our situation? (pause) Does (0,0) make sense in our situation? (pause) If you had zero length would you have zero period?” It was almost as if every time she tried, she had thought through how to better ask the question to get them where they needed to be, but not by taking them there herself. The students answered to each other, not to her, “No!” Leslie watched for a few seconds more, before resuming her tour of the room.

The graphs that the students constructed looked like $y = x^2$, a parabola, and using that recognition, or whatever relationship they saw, the lab paper encouraged students to figure out the proportional reasoning that this relationship implied (i.e., if y increases by so much then x will increase by this amount). Leslie asked a group about the number 25 she saw in their best-fit line, and helped a student pick apart their proportional reasoning:

> Leslie: "…that—there's a 25 in there, so really what's *y* equals five *x* squared?"
>
> Student: "So the original number squared; it's the original number squared, so if the original is doubled, the original becomes original times four."

That was it! The relationship was with period squared, not just period. The student went back to work.

With twenty minutes left, the students tested their predictions with the 2-meter bowling-ball pendulum. The whole class could have measured the period just once as a group, but there was enough time for each group to try and the students seemed to be having fun. Leslie told them to hold their lab papers. With all the labs they had been doing, she already had too many to grade that night. As the class wound down towards dismissal, Leslie talked casually with some students about her pet fish and reminded them to clean up the lab materials. "I don't want to have to clean up after you!" Some students were still talking about the pattern. It really looked linear until the extreme, so, without testing extreme values, some groups believed it was linear. Some students continued to debate and write their conclusions all the way until the bell. When it rang Leslie looked up, surprised, and shouted, "Goodbye!" as the students filed out into the last September afternoon of the year.

Leslie would be at school for six and a half more hours until the last parents left Back-to-School Night that evening. The graphs on the board remained as evidence of the kinds of reasoning that students were doing in class, and the big pendulum remained as a conversation starter with parents. (See Appendix A5.7 for another look into Leslie's Back-to-School Night school day.)

5.4.2 Cognitive-Instructional Resources

Leslie had many cognitive resources (coherent patterns of thought and action) that influenced her physics teaching actions and priorities. Not all of these were present or explicit in every lab, but they were present in at least some of the labs on some of the days. After watching her teach nearly 70 hours in 45 classes, I have identified the following resources, and Leslie gave them her approval in a member check.

First, Leslie required good-quality data collection so that students could make sense of a phenomenon. Data was paramount for Leslie; she wanted students to collect and analyze data to reach conclusions in the classroom laboratory. She wanted students to use appropriate empirical techniques (only one independent variable and appropriate data collection methods to minimize error, including at least five variable values to make a decent pattern and three trials per value to reduce random error) because then she could trust that the appropriate relationships would show up in almost any lab they were doing in high school.

Leslie also spent a month at the beginning of the school year scaffolding graphical interpretation so that students would seek graphical patterns to make sense of lab data, paying attention to dimensional analysis when analyzing a graph and examining y-intercepts for meaning. These standards reflected Leslie's insistence on acceptable minimum data for sense-making in inquiry but also showed how she intended students to learn to trust the method. "[By the last lab in the patterns unit] they're totally confused, but they feel confident in their method, and that's the point. The point is to make them understand how to create a graph, [and] how to interpret that, and it's the data that leads the way."

Second, Leslie required student reasoning by not giving away the solution steps. Leslie said that when she was in high school, she "was taught very formulaic ways of getting to answers" using very few labs or correct problem-solving steps. In contrast, Leslie did not teach students formulaic ways. She answered student questions with questions, demanding that students reason for themselves instead of relying on her reasoning ("Do YOU think it's important?"). Resources that contribute to this sort of teaching, such as an aversion to formulaic problem solving, helped her stay committed to encouraging students to answer their own questions.

In inquiry labs, even Level 2 inquiry, Leslie insisted that students figure out ways to do the work themselves in groups instead of telling them how to do it. As support, she gave them sense-making tools like pattern recognition, dimensional analysis, and deadlines. She said, about the iPhone PBL they did in the year before this study, "We gave suggested benchmarks, like, 'Hey, by the end of today you should probably have a plan set and maybe a materials list,' just because they need that."

Collaborative norms are just as important here, and Leslie taught collaboration intentionally, emphasizing the role of collaboration in science world-wide—"You are NASA, you are the European Space Agency, you're the Russian Space Agency and you're the Japanese Space Agency. Who will you ask to help you solve this problem?"—and in the classroom. "Is there consensus on this?" was a common classroom refrain.

Leslie provided time for students to make sense of their observations. In discussing how her projects have evolved over time, Leslie said, "They are more student-led, but the kids are the ones in charge of their learning, or the kids are the ones that are able to move the process forward. Because of that, they learn a lot more through their mistakes and through their successes, but it does take longer." Maybe it goes without saying that one major constraint in teaching is time, and in this quote Leslie acknowledged that by not giving away the answer, the instructional process will take longer than just telling students answers or procedures. Leslie was willing to give up precious time to teach in this longer, student sense-making way of learning.

Third, Leslie off-loaded authority to help maintain student-centeredness. Leslie's approach to teaching physics was less teacher-centered than more typical direct instruction methods. Leslie celebrated the authority that students had and relished seeing her students make sense on their own and with each other. Her classroom environment simmered and hummed without her having to be in obvious control. "I love how much I'm quiet in a day…it's just very student-centered." Leslie estimated (and I concur after a school year of sampled observations) that she spent only up to one-sixth of her instructional time talking directly to the students. Leslie also had some well-practiced routines to encourage student-centeredness.

Leslie had many routines and skills to maintain student centeredness in her classroom. For example: Leslie was quiet, actively quiet, meaning that Leslie would fall silent and listen. She was aware of doing it, and she did it on purpose. This is more than just “wait time,” typically three to five whole seconds of valuable, uninterrupted student thinking (Rowe, 1986). This was tens of minutes, sometimes up to thirty minutes or more that a group could work with no interaction with the teacher. Though quiet, Leslie was paying close attention to the group and she would chime in as necessary, like when the period was not being divided by four in the pendulum-length lab, or when she noticed an issue in squaring the period in the proportional reasoning.

Leslie had many other routines to keep things student-centered including emphasizing student-to-student reasoning and interaction. She described the other five-sixths of her classroom where she was not talking as, “Talk to your neighbor, answer this question in your groups” or “Go off in your lab tables, or go off to your groups, or whatever.” With student-student reasoning, the minds of all the students could stay engaged, and every pair would have the opportunity to reason out their thoughts, keeping their processing in the center of their learning experience. Turning sense-making over to students also required that students solidify information on their own, thus reducing the amount of top-down authority the teacher has to provide.

Many of Leslie's well-practiced classroom routines seemed to set up students to rely on themselves, instead of on her as an expert. Her routines increased shared knowledge and reduced the need for the teacher to be the only expert authority in the room. During labs, Leslie seemed almost entirely passive, walking away from students to listen from afar, so that students were not influenced by her presence. This hands-off teaching method of facilitation could have felt like abandoning students to flail or sink. So to support students while keeping the authority in their hands, Leslie regularly deployed tools such as technical resource sheets, rubrics, group collaborative norms, and teacher check-ins.

Composing technical resource sheets for lab equipment enabled students to learn on their own time to work with a particular piece of equipment. The sheet was usually an innocuous piece of paper taped to the lab bench or computer interface. It might have seemed like part of the experimental system and not tied to Leslie's instructive role, but she wrote each sheet for the specific lab based on her previous teaching experience. The technical document effectively eliminated the traditional "stand around and watch me do this" model of equipment demonstration.

There was a good example of this on the third day of the Pumpkin Chunkin' Challenge. A student walked up to Leslie to ask her how to do the lab with a video camera. Leslie tossed the responsibility to troubleshoot back onto the student. "Where are your free-fall directions? I think the free-fall directions say so." Leslie had planned for their self-sufficiency, and she was not going to undermine that planning by helping them with something as simple as lab equipment.

Leslie also advocated a small focus-group type of equipment demonstration. Several students, but just one from each group, would come together to the back of the room to hear a lab equipment briefing, and then they each would teach their group. Even though the demonstration was available for all, some students may not have needed it. Instead, based on their preference and needs, they could have learned about the equipment from interacting with it. These options provided a very differentiated approach to lab instructions, and this showed that Leslie was comfortable with less scripted lab procedures.

Rubrics give a scaffolded structure of what the students are responsible for and what high achievement should look like or include. Leslie's rubric removed a bunch of teacher-centered explaining time and created more time for students to do the lab (a precious commodity that could be a limiting resource for doing labs in the first place). Her rubric could be altered from class to class to focus on various elements, such as demanding more error analysis in IB physics class than in regular physics class.

Talking to neighbors and reaching consensus kept students accountable for their own reasoning, and quick teacher check-ins allowed her to monitor groups without hovering. Teacher check-ins were usually inserted into labs at transition points. After students designed the lab, Leslie would ask to hear each group's idea, creating a need for students to be able to talk about their project at a meta level, such as, "What are you doing, and why? What do you think will happen? What will you measure, and how? How will you analyze the data you gather?" A teacher check-in could feel teacher-centered ("I must okay this" or "No, do it this way instead"), but Leslie was careful to keep it student-centered by asking probing questions and sending students back to think it over again in their group, instead of sense-making with her.

Effectively, these tools freed up Leslie in the lab space; she did not have to run from group to group assisting each group individually. Instead, she could observe her students talking and moving and she could consult or probe as she saw fit. Her attention to the whole room and the larger task of inquiry overall could be wider than if she were focused on helping put out fires in individual groups. And together, using quiet observation of the students working, encouraging student exploration, and providing scaffolds such as technical resource sheets, rubrics, check-ins, and facilitating group conversation maintained a high level of student-centeredness that Leslie preferred.

5.4.3 Epistemological Resources

Aspects of Leslie's physics epistemology came together to help animate her inquiry instruction. This section describes some resources called up in that instruction which were also flagged as productive in her engineering-design instruction. These may or may not represent her gross physics epistemology well, or even the resources that she calls up most commonly, but they were present in both situations.

Leslie encouraged students to construct their own knowledge. Leslie withheld direct answers and wanted students to work with data or empirical observations because fundamentally she thought learning happens when students construct understandings from experiences, communication, and reflection, indicating that she held a constructivist-learning stance. A constructivist stance is comprised of many smaller resources, including, perhaps, “knowledge as fabricated stuff.” Leslie seemed to call up the “constructivist stance” very readily, so here it is treated as a compound resource in its own right instead of trying to unpack it down to its parts. Certainly, at times other conflicting stances were visible, but frequently Leslie seemed to have a strongly constructivist stance.

Leslie believed knowledge should be constructed by sense-making with phenomena before instruction. Unlike the way she learned physics in high school, her physics classes involved lots of pattern-seeking lab activities. For Leslie, students could learn physics knowledge by observing and manipulating phenomena and then making sense of patterns in the observations. Equations make up a lot of physics content knowledge, but Leslie rarely just told students an equation. Instead, Leslie had students develop the equations and rules, usually from observation and in lab groups. Table 5.1 gives some examples.

Leslie frequently had students touch phenomena as a hook, sort of like showing a video. But just using one’s hands is not inquiry learning; inquiry learning involves students making sense of an observed phenomenon and developing understandings from asking questions of the phenomenon, manipulating the experience to see a pattern, naming the pattern and comparing it to other relationships and expectations, and making it usable in other contexts. It felt like hands-on learning was normal and expected in Leslie's class. She seemed to believe that the tactile experiences of doing helped build knowledge. This aligns with the constructivist epistemology of knowledge as fabricated stuff, because she thought students would build knowledge when they saw proofs and counterexamples in the actual phenomenon in front of them.

Activity	Inquiry Level	Evidence
Inquiry Cube	Level 3	Question given—what's on the bottom side? Predict the 6th side and justify your prediction.
Pendulum Lab I	Level 3	Question provided—what's the effect of mass on the period? Equipment and general procedures provided—observe the pendulum for various masses. No directions given about other variables, how many swings to time, or trials to execute etc. (Later she told her students she enjoyed watching them try to keep the drop angle constant even though it would not have mattered.) Led to discussion about uncertainty and error .
Wiggler Lab	Level 2	Question and procedures given—what's the relationship between wavelength and frequency? What happens when you change the tension? Observe wavelength for many frequencies, graph, state relationship. Change tension of string. Observe wavelength for many frequencies, graph, state relationship. From graphs, use dimensional analysis to figure out what the slopes mean. Determine physical factors.

Table 5.1 A Sample of Leslie's Level 2 and 3 Inquiry Labs

There is a cost to inquiry instruction, however. Doing labs takes more time than lecturing content. (I'm not going to comment on the relative efficacy of these two methods). Yet in Leslie's negotiation between taking up time and allowing for constructivist learning, the resource that frequently won out and allowed her to take the time to do a lab was Leslie's resource of "knowledge as fabricated stuff" steering her toward allowing students the time to learn by doing.

Student groups were at the heart of Leslie's instructional methods, and she made it clear that the whole group mattered. She scaffolded group norms that valued all contributions, such as reaching group consensus and asking for differing opinions. Teams members were all responsible to one another before they were responsible to her. Leslie said, "I love when students talk to each other because [students] have a language that I do not always have." She went on to say that students explaining to one another were more effective than she could be and that their explaining also strengthened their learning. Leslie contrasted good group work—where ideas were challenged, new understandings were mutually formed, and it was okay to struggle—with "brain sucking"—where a student in a group just followed along and reported the group (or another group member's) conclusions but did not understand the material.

Leslie's emphasis on groups and collaboration in physics learning points to a possible epistemology of physics learning, that students learn by making sense in their peer groups, or that knowledge is stuff fabricated by many people together. This reveals a very social constructivist stance, that the knowledge forms and emerges as students reason together, out loud, about phenomena they are seeing. The teacher can help guide the reasoning with prompts, but it mostly happens within the groups. Leslie seemed to believe that learning is enriched by novel contexts and that learning is demonstrated by transfer to new applications. She brought in examples from non-traditional realms for students to learn from and apply learning to. For instance, she used the United States judicial system to help give gravitas to the importance of communicating claims, and the Mars rover to talk about vector addition. Regarding her own physics learning, she remembered, “It was very, very formulaic, and it was hard to see applications past what we were doing in the classroom. It was hard for me to extrapolate it into other scenarios.” Leslie wanted to make sure that her students would be able to extrapolate, so she was constantly pulling in other scenarios and demanding students could transfer what they were learning.

Leslie’s appreciation for context in constructing knowledge may also mean she believed learning is increased when framed in contexts. For instance, Leslie used her popular Monday Musings tradition (a weekly segment in which she discussed a current event or another aspect of life with her physics students) to expose students to connections between physics and the wider world. While Monday Musings might have seemed tangential to physics class, Leslie turned them into hooks for the day’s lesson. Sometimes she acted surprised that the day’s lesson and the Musing were related, but the students seemed to know the Musing would be a hook and learned to crave that. I heard students who were absent on a Monday ask what the Musing was.

I believe she did Monday Musings because she believed that students would think more deeply about the physics content when their interest is piqued by a related event or context. At times, that was all context was, a hook to gather interest. Later, in engineering design, Leslie hoped that hook would evolve into another student-chosen context, such as “what else could we launch and why?” in the Pumpkin Chunkin’ Challenge and “what else could we want to drop slowly?” in the Parachute Challenge.

Leslie seemed to hold a growth mindset regarding her students’ learning. A growth mindset means that intelligence is not innate; instead it is possible to develop intelligence over time. Similarly, learning is not “accomplished” or “completed” at any point. Learning happens along a continuum, and any movement on the continuum, forward or back, is advantageous because it informs the next steps in learning and continues the development of intellect. Leslie followed some practices that indicated she had a growth mindset towards learning. She believed that ability in physics, teaching, and general learning can be developed; she actively embraced failure as a way to learn; she allowed students to remediate poor tests and quizzes in all of her classes; and she used a standards-based grading method in her IB physics classes. (Leslie would have liked to use standards-based grading in general-level physics as well, but she faced resistance from a co-planning peer.)

Leslie appreciated that other contexts for learning can emerge without planning or in informal settings. She encouraged her students to “Have adventures! Make good choices!” when they left her classroom on Fridays. Of course, adventure is fun and engaging, but it can also be instructive. If you are not careful, you might learn something while you are off having fun. Adventure sometimes leads to risk, struggle, and even danger; but struggle can be productive for learning, too.

Leslie seemed to value mental struggle in the classroom and encouraged students to work productively near frustration or at the top of their zone of proximal development instead of teaching easy ways through the struggle. Teacher moves like “puzzle it out” pointed to her appreciation for the struggle that students go through as they learn and her conscious effort to help students remain critical of every conclusion they reach.

Leslie also seemed to believe in productive struggle for teacher learning. I saw evidence for this in her interest in pushing herself professionally through new, sometimes uncomfortable situations, and in her acknowledgement that she could grow from working with difficult students. In October, Leslie and I were talking at lunch after a new seating arrangement led to a particularly chatty (and productive) class. About some chatty boys in class, she said, “It’s okay. We’re going to stretch each other…We’re going to learn how to deal with people we don’t know how to deal with.” Her comment reveals a metacognitive understanding that she did not quite know how to deal with the chatty boys yet, but that there would be value in learning how to do so. Table 5.2 summarizes Leslie’s cognitive-instructional and epistemological resources described above.

Leslie’s Cognitive-Instructional Resources
Leslie required good data and student pattern recognition.
Leslie required and supported student reasoning.
Leslie gave up teacher authority to help increase student-centeredness.
Leslie’s Epistemological Resources
Leslie valued students’ individual and social construction of knowledge.
Leslie valued learning in contexts, even indirect ones.
Leslie valued struggle and failure as productive for learning.

Table 5.2 Resources Identified in Leslie’s Non-Engineering Instruction

5.4.4 These Resources are Related to Inquiry Instruction

Not providing direct answers, requiring student autonomy, and sense-making tie directly to open scientific inquiry instruction (Rezba et al., 1998). Inquiry instruction means students have opportunities to take on authority for their own learning, to make decisions about what to learn and why, and to behave more like real scientists (National Research Council, 1996). In her labs, Leslie used full open inquiry (level 4), guided inquiry (level 3), and structured inquiry (level 2), with most laboratory activities falling in the level 2-3 range. For Leslie, open inquiry in physics meant asking students to discover something about a material, phenomenon, or topic of their own choosing, and then monitoring, not guiding, their progression through research, experiment planning, experimenting, analysis, and sense-making in the lab. In Leslie’s use of level 2 inquiry, she embodied her desire for limited teacher involvement to increase student agency. She described this desire in her first interview: “[I like] the freedom to do projects that take more time, because they are more student-led, but the kids are the ones in charge of their learning, or the kids are the ones that are able to move the process forward. Because of that, they learn a lot more through their mistakes and through their successes.” Even Leslie’s support tools, such as technical information sheets about lab equipment, maintained level 3 inquiry. None provided procedures or step-by-step instructions for completing an investigation, they just gave tools for the students to “move the process forward.”

Leslie told me one of her favorite open-inquiry memories, one that exemplified how stepping back allowed exciting student engagement and discovery. One year, she simply told her students to investigate something about spaghetti, and gave them nearly limitless dried spaghetti pasta to use. The students manipulated and tested it extensively, some even lit it on fire to see how much thermal energy different varieties would produce, a way to measure caloric energy stored within the material. Some teachers might have heard that “light it on fire” research idea from a student and dismissed it as ridiculous teenage pyromania, but not Leslie. She just asked them to make sure they could quantify their variables and reminded them of the rubric (Appendix 5.9). Leslie frequently used the phrase “lighting spaghetti on fire” as shorthand for students doing meaningful, independent, open inquiry.

The resources mentioned above, that Leslie called upon in her physics teaching, were also productive in various combinations in her engineering-design instruction. During her Pumpkin Chunkin’ engineering design, Leslie faced a moment of student divergent thinking that caused her to question how she was teaching engineering design. In this episode, Leslie tussled with some elements of engineering-design instruction—time demands, divergent thinking, issues of authority, and how to scaffold physics content. Leslie drew upon her epistemic and cognitive resources to support her mission.

The following narrative is based on my data—observations, field notes from class, video and audio transcription, memos, inferences—and was reviewed with Leslie in two member checks in June and November 2016. Leslie has also read and provided feedback and approval of this narrative and chapter. I have used quotation marks to report exact language. In places where quotation marks are not used, I attempted to fill in the story by "speaking" for Leslie, using information about her concerns and motivations from conversations about this specific episode, and making inferences from knowing how she thinks more generally. These places, such as in "Setting the Context," have also been reviewed by Leslie.

5.5 The Spoon Incident: Resources in Engineering-Design Instruction

Leslie's first day teaching engineering design raised several fears. What if students were going too wild? What if she was teaching it wrong? Leslie called upon the resources she used in inquiry facilitation—levels 2, 3, and 4—to help her get past those concerns and facilitate a student-centered engineering design challenge.

In November, Leslie asked me to help her think through an engineering design challenge based on the Pumpkin Chunkin,' which is a real event held every year in Delaware. Competitors try to shoot pumpkins as far as possible using cannons, catapults, and trebuchets. Leslie had some exposure to the ideas and methods of engineering design in our first group meeting in October, but this was the first time anyone in the group was really planning to teach anything related to engineering design in their physics class. Leslie essentially planned this challenge alone with some input from me, so this episode reflects her decisions more than the those of the group of three Merlin teachers.

Leslie planned to use the challenge to get students interested in filming a projectile, a candy pumpkin, and doing video analysis of the falling body to learn about free fall. The account below is based on Leslie's fifth-period general physics class, which was her first of three iterations of this instruction. She also taught this to her 6th and 7th periods general physics classes. Leslie was fairly consistent across the three periods. In period 5 she said, "All you need is a pencil and a brain full of curiosity." In period 6 she said, "All you need is a pencil and a brain." Once she established her probing questions in 5th period she retained them for the other periods. I focused on the 5th period, however, because the lunchtime conversation about her "mental work" occurred immediately after 5th period.

5.5.1 The Pumpkin Chunkin' Challenge

Leslie's 5th period was not an elite engineering class and was not Honors, AP, or IB. It was general physics for students considered on or below grade-level in math. This class did not require a standardized test at the end of the year, so sometimes students took it who wanted a science credit but did not want to risk the credit on test performance. Fifth period had a full range of engaged and unengaged students, a dozen or so students with accommodations, and plenty of chatty students, and it was not even Leslie's most obedient class of the year. This was simply a class of average high-school juniors and seniors about to go on a journey into engineering design.

5.5.1.1 “All You Need Today is a Pencil and a Brain Full of Curiosity”

“Good morning wonderfuls!” Leslie greeted her students as they came in on a Monday morning in late November. Leslie’s room was in its usual state of neat but cluttered, with a sawed-in-half cello hanging on the wall, a fake fish tank on her desk (she jokes that the fish, Chuck, is real), and the largest rubber band ball you have seen in real life. It was the start of a short, three-day school week before the four-day Thanksgiving weekend. Many classes would be showing movies, having potluck parties, or doing softer, no-content stuff like writing a thank-you letter to someone they loved. When the students walked in and read “Catapult Challenge” on the board, they might have thought that this was going to be soft, too.

Leslie set an open-minded tone; “All you need today is a pencil and a brain full of curiosity.” Actually their whole brain, all the skills and knowledge they had learned in physics, and their past 12 years of school mathematics, would be required of them. Leslie struck a balance between asking much from the students and making it feel natural to do that.

Leslie laid out the context for the day’s activity. She lowered her voice and got as serious and as playful as a campfire ghost story. “We do have a Monday Musings this morning,” she purred, cuing students to tune in to one of their favorite classroom routines. She spun a short tale about farmers with a surplus of pumpkins, saying, “People just aren’t carving like they used to, not baking pies like they used to.” So, she said, the farmers wondered together about the pumpkins, “What if we could make a contraption to make them *fly*?” Whispers rippled around the room, “Pumpkin Chunkin’!” Ms. Knope did not confirm the whispers; she just lowered her chin and gave them her ghost-story-telling, face-over-a-flashlight eyes. It was palpably exciting!

Leslie played two videos of pumpkin chunkers from the Discovery Channel, a trebuchet “whipper” and an air cannon. Leslie asked if anyone knew the difference between a catapult and a trebuchet. A student gave a pretty solid answer, from which Leslie picked out the keyword “counterweight” for trebuchet. A second student expanded on the first explanation adding in “tension to hold the potential energy.” Leslie seemed fine with their understandings thus far. “Good. Fair, fair, fair,” she said, and moved right along without changing or correcting their ideas.

Students reacted during and after the videos, and Leslie allowed their excitement to burst out. I heard, “That was sick!” and “Can we watch it again, please?” After the videos, she told them they would be designing a machine to compete in the Chunkin,’ but they could design it for any stakeholder they found provocative. “As engineers, and we’re stepping into the role today…we first need to define our problem. If we don’t know what that is, then we don’t know where to start.” Her words “as engineers” were laced with another level of seriousness, followed by an emphatic pause.

Leslie said, “I’m going to pass out a packet to think our way through this,” and she handed out a document with boxes on the front (Appendix 5.4). This was a signal that some kind of student activity was about to happen; she usually provided some kind of handout for labs, but not for notes.

Leslie: We’re going to be working our way through kind of the engineering design process today. And all good engineering problems start, or designs start, by really understanding the problem at hand. So talk in your groups. This first little box here, after watching the videos, what is your initial understanding of the problem that we have right now? Talk in your groups. One minute.

Leslie did not stunt the class’s excitement by making students listen quietly while she went over the worksheet. The boxes on the paper were laced with new engineering vocabulary like “criteria,” “constraint,” “stakeholder,” and “problem statement;” but she did not stop to define these terms. Instead, she threw the responsibility of reasoning through their meaning onto the students. She told them to “talk in your groups” instead of “write this down.” Leslie wanted the meanings of the engineering design words to emerge from the context of the videos she had played, combined with the understandings students already had of those words, not from her defining them. Later, she could clarify if they missed the mark, but she was pretty confident they could move through it together, maintaining the excitement from the videos.

By this time in the school year, late November, a culture of student talk was well established, and the room quickly started humming with student voices. As the students spoke, she walked around and fielded, but did not directly answer, their questions. For instance, a student asked, “Ms. Knope? Are we focusing on distance or accuracy today?” Leslie usually would not answer this kind of question directly, especially not after she told the students to puzzle that out in their groups. Instead, she would just say, “What’s your initial understanding of the problem?” But on this day, she seemed a little nervous and tensed up. This was the first time she had done this engineering-design thing. What if the students could not articulate the problem? What if there were too many options, or too many distractors in the videos and in their whole-class conversation, to focus on what the challenge required? She wanted the students to be able to state the problem in their own words so they would get invested in it, but she also did not want them wandering off the path she was planning for. This was a lesson on free fall, after all, and she needed them to get a pumpkin in the air for video analysis. Leslie paused a beat and collected herself. Her response was a little more nervous than usual, but she was able help the student without telling him what to do.

Leslie: Um, what does the problem seem to state?

Student: I don’t know.

Leslie: What does the problem—does the problem include both or one?

Student: Both.

Leslie: Ok… .

Student: Er, it’s more of an “either or” maybe…[trails off].

Leslie: [Excitedly,] Ok, so make sure to write that down!

This student did not really come to a single answer, but Leslie did not have a preferred single answer in her head. She showed both videos because shooting for distance and accuracy were both going to demonstrate free fall, and so they were both appropriate content-wise. For Leslie, it would have been fine if the student said, make it go far, go high, hit a target, hit the state line, break a window, go a mile, or any combination of these. What satisfied her and why she walked away, was that he reasoned with evidence from both videos, which showed he was thinking about the problem based on the evidence he had. In this brief interaction, Leslie provided some minimal scaffolding, but it was sufficient to move the student from confusion and a passive stance ("I don't know") to realizing there were two aims in the real scenario videos, and to making a sentence to describe his options as "either or." That reasoning and engagement was what she wanted to see. She didn't decide which of these options students could choose; she planned for students to pick their own agenda in this challenge to keep their interest and buy-in high.

The students used criteria and constraints before Leslie defined the terms. To do so, Leslie told the class to move on to the next set of boxes on the handout (boxes labeled "criteria" and "constraints") and asked the students to identify the "qualifying parameters, qualifying things your design must do to be even able to compete" and to decide for whom they would design their catapult. Leslie said, "Turn to your group and talk about it," and heads swiveled to the center of each table and began to chatter again. Leslie walked around the room, listening. Sometimes she stopped to talk, and sometimes she just listened and moved on. She avoided interrupting the student chatter just like it was a regular class day. The students listed the requirements from the videos, eight- to ten-pound pumpkin, etc.

Next, students shared their responses, and Leslie led them through a refinement of the vocabulary, criteria, and constraints. Leslie stiffened when she said, "I'm going to talk to you about the difference between these two words [criteria and constraints] and then we're going to look at exactly what falls under that. I need your attention this way please." Leslie didn't lecture often in this class, and as she talked through definitions of criteria and constraint, I noted how awkward it felt in my field notes. "Some tripping over words here… Didn't pause for questions, just went right through." This was noteworthy because Leslie was usually smooth in her delivery and relied heavily on student input, but getting these definitions down correctly was tripping her up.

At lunch, Leslie and I talked about this. She said she had been intimidated about getting it "right" during class. She said that during the lesson she was stressed about "trying to follow rules, trying to, um, present this according to those invisible rules that I just like create in my mind. And so it's like, 'Okay, what vocabulary do I need to use? What is legal? What's illegal when it comes to this project?' " Leslie perceived rigid rules for how to present the vocabulary, but she had already asked the students to do sense-making before going over the formal definitions. In the moment, she had held the nervous formal stuff for after the student reasoning. During reflection, she sort of forgot and only remembered her anxiety about getting it right. She described the whole introduction as "a little worksheet-y";

> Leslie: It just felt kind of like, even though the videos were good, I think they were just kind of like, "Ehhh what is this?" Like, "What are we writing?" and like, "Why are we writing this?" You know? And it just

> felt kind of ehhh. I wonder if to them it felt a little bit worksheet-y. [chuckles] Worksheet-y. Ugh!

I thought the whole lesson thus far had been engaging, active, and focused on what students could take from the videos and contest context; but for Leslie, it was still stressful because of pressure from her self-imposed "rules."

5.5.1.2 Scaffolding Creative Context Building

Next, the students turned to their groups to devise "refined problem statements" by synthesizing and choosing stakeholders and their goals, and by forming a sentence to state their own role and their own goals. Leslie scaffolded the refined problem statement on the paper by demanding they include elements of contextual creativity (invent a stakeholder) and formal elements of design (pick a major criterion from the many things that you could try to optimize about a pumpkin launcher, such as accuracy, distance, speed, all suggested in the videos). Then they shared their refined problem statements. My field notes documented what they chose to design. "All of the groups in this class will be trying to make a pumpkin go as far as possible. I guess that hook about the real Pumpkin Chunkin' pumpkins going so far off range that they can't get insurance any more worked!"

The variety of scenarios and stakeholders chosen was broad. She told them to be as creative as they wanted, and some of them took her up on it. A few groups said they were building a catapult for Ms. Knope, and a few said for the students themselves. But some defined unlikely or fictitious stakeholders, such as Jack Skellington the Pumpkin King from the *Nightmare Before Christmas* movie, Soviet

Russia, the US military, etc. As they shared, Leslie nodded and said, “Good, good. Okay, next.”

Although Leslie was listening and encouraging, and withholding judgment, she was also hustling them along in an uncommon way; and I noted that she seemed nervous. Later, at lunch, she explained that while the students had been sharing their ideas she was worried that they might be doing the engineering design wrong. She worried whether the problem statements were adequate. For instance, was it okay that they were designing for themselves? Did stakeholders have to be other people? Could they choose Soviet Russia if they knew nothing about Soviet Russia’s wants and needs? And what about the fact that they had all chosen to go for longest launch? Did that reflect on the way that she presented the problem? Did it make the challenge weaker overall?

Leslie reflected, “That’s why it feels so uncomfortable, there’s actually a ton of freedom in this project.” So how did she get past that discomfort? In the moment, she seemed uncomfortable, but she still respected their choices. She did not limit anyone’s creativity or tell them to tone it down. She relied on her feeling that these contexts would be helpful, that the students could be trusted to learn from doing, and that soon they would interact with a catapult to capture free fall and that would be valuable.

5.5.1.3 Design Exploration, Testing

After the students shared their refined problem statements, Leslie asked them to switch into the design exploration phase. Her attitude eased; “Go ahead and flip the page. This is where the good times get going." On the page was a picture of a rudimentary popsicle stick catapult (see Figure 5.4). Leslie explained that she had tried many designs at home and had chosen this one for them to optimize. Actually she had chosen that design to improve because it gave the students somewhere to start and offered many potential ways to change it. They could increase the number of sticks in the stack under the lever arm, move the stack along the lever arm, move the spoon along the lever arm, change the tension in the lever arm's connector (rubber bands), or make many other changes in the design.

Quickly, Leslie passed out a model of the starting design to each table. At that moment, the energy in the room increased a lot. Students were excited to touch the models. Students watched each other's hands flick the spoon back, and they instinctively reached in to hold down the base while their peer pulled the spoon back to tap the desk under it. They did not have a projectile yet but were told that when they had devised their optimization experiment, they could collect any materials they needed from the front: more popsicle sticks, rubber bands, meter sticks, and a tiny candy pumpkin projectile. (Leslie had NOT defined "optimize" or "optimization" yet.)

Leslie had known what would happen; she knew that getting their hands-on the model would create lively energy. That was one reason she waited to hand them the models; she wanted them to focus on defining the problem before being tempted to launch the catapult. Designing this physical product was inherently hands-on, and quantitative testing for optimization meant that the students would have to do hands-on modeling and experimentation to test and justify their design decisions. Even while scared about doing the engineering-design instruction poorly, Leslie called upon her open inquiry facilitation resources and she demanded that each group select just one variable to optimize. The students would design an improved catapult and test its function on the variable they selected. Leslie trusted sound data collection to lead to useful conclusions in inquiry instruction, so here too she felt that collecting data well could lead to learning.

Now the students had to pick out what they would change about the design and how they would measure it to see the effect on the distance the pumpkins flew. Students began to modify their catapults as they decided on which variable to change. No formal hypotheses were written down. Instead, the students were reasoning rapidly and playing out their hunches about what might work with the catapult in their hands. This process looked like what might be called tinkering or rapid prototyping.

The groups' ideas diverged widely. One group was interested in making a much longer lever arm, and they taped some sticks into a long, three-ply arm. One group cut the handle off of the plastic spoon so their testing could start with the spoon's bowl over the fulcrum. One group stacked more and more popsicle sticks on the fulcrum until the upper arm came out of its tether at the vertex. So they tried again with different rubber bands at the vertex, and it broke again. When that happened, they decided that was the upper limit and that their experiment would work backwards, taking data as the stack lowered.

5.5.1.4 “Total chaos”

I saw Leslie looking around the room at all this tinkering in a tempered panic. Her eyes were wide as she watched her students. They were not even to the part she thought would be hard—taking video, importing the video, setting the scale, and making motion maps of the pumpkin falling in the y-direction. Instead, it was the snapping sticks, the spoons coming off the apparatus and being cut to a stub, and the extra long lever arm flying as someone whacked one end of it that captured her attention. Leslie scanned the room and surveyed all of these things happening at once. Months later on Leslie remembered this part of the lesson vividly.

> Leslie: I was really wigged out by what was happening. It was total chaos. Stress to me doesn’t come from things failing. Like, things failing miserably, you know, it happens, that can make for like a tiring day, but to me that’s not necessarily stressful, um, just because you know kids, like, shrug it off and like move forward. But stress to me comes not because you intimidate me in any way, but because…there’s like some expectation of what this process looks like, not because you like negatively project that. This is all like internal projection.

It was not that she thought the kids would fail, and even if they had it would have been okay. No, she was nervous again that students were violating engineering codes of conduct, and specifically, that I was going to think she had done a poor job of teaching them to try engineering design. She explained that seeing the students’ interpretation made her doubt what she was doing.

> Leslie: When those kids just took the spoon off the catapult my heart was like 'hhhhhuuuuh! [sharp inhale] Is this allowed? Is this okay that they're doing this? Why are they doing this? Do like, are they not realizing something that I should be making them realize? Are they like missing an entire aspect that they should be comprehending? Do I need to be addressing this in any way or do I need to let it go free?'

Her last question, "Do I need to be addressing this in any way or do I need to let it go free?" put her active processing at odds with the way she normally teaches inquiry—allowing student choice to override everything, even wrong answers, as long as the appropriate scientific inquiry conventions were followed. Here, in engineering design, she was not sure that the students were following the analogous appropriate engineering conventions, so she could not be certain if they were going free within sight of good engineering design or not.

This situation was so unlike the learning expectations Leslie normally had. Normally, setting fire to spaghetti in her physics inquiry labs is okay for her because it indulges student interest and helps them learn by constructing knowledge from experience and inquiry. But here, she was worried that she should not follow her natural inclination to let the kids "go free" to learn about the engineering design process itself. Would taking the arm off of the catapult help them to learn engineering design like lighting spaghetti can help them learn physics? Should she have just told them what to do? Fretting about whether she was doing it right, and whether her usual constructivist instincts held for engineering design learning, caused her stress during instruction.

In the moment, it was Leslie's resources—her faith in student construction of knowledge through seeing, doing, and reasoning as well as her epistemology of physics knowledge, the knowledge as fabricated stuff epistemology—that she relied upon to get her through the stress.

> Leslie: Do I need to be addressing this in any way or do I need to let it go free?
>
> Katey: Did you address it to them?
>
> Leslie: I did not. I just asked them—No, I didn't.

She decided in the moment to let them go free, drawing upon the open-inquiry facilitation resources she used in her wildest spaghetti-burning moments: just make sure the science is sound, then they will still be learning something based in data. Instead of saying, "that is not allowed" because it was making her uncomfortable, she instead let it happen and hoped that students would learn some engineering from doing it.

So although her eyes were wide with fear, Leslie retained her usual, well-practiced, laboratory-facilitation stance; she watched, answered questions with questions, and let the students stay firmly behind the wheel of the ship. Leslie was not certain where exactly the ship should be headed, but she knew the students should be at the helm, so she left them there. She focused her thoughts on the experiments that would come next in optimization.

During the class, Leslie came over to whisper to me about how she figured some of the most divergent ideas would run aground when the students realized that they still had to use proper experimental procedures to reach a conclusion about their catapults. My audio recorder did not capture this moment, but my field notes said, "[Leslie] conferences with me: she thinks the students don't trust her initial design—they are diverging widely but might just be realizing that it's hard to keep any variables constant." Some groups, she noticed, were changing multiple variables and thus were not going to be able to make a well-reasoned conclusion about their catapult or to finish her inquiry requirements adequately. But Leslie did not jump in immediately, instead, she looked for signs that they might recognize the need to isolate one variable, and when she saw that recognition she came to share her observation with me.

As she did at times in inquiry labs, Leslie allowed some work she was not completely pleased with to go forward. One group was trying to find a way to make their design look "militaristic." Leslie asked them, "What's your criteria?"

Student: [It] has to look cool.

Leslie: How is "cool" going to be defined?

Student: [By] us. It's really based on what looks awesome [to us].

Leslie: Okay, qualify that and then write it down.

Though "militaristic" was inadequate as a quantifiable variable, Leslie found a middle ground. She told them to, "qualify that and then write it down." It might not be perfect quantifiable data, but if they could find some characteristics that they were going to “test” their design against, that would be better than not doing it. This was different than a teacher who might have just said, “Nope, that won’t work here. You have to pick something else.” She wanted them to come up with the qualities that would be “awesome” for a militaristic weapon. She was allowing them to contextualize a physics task, using student-driven decisions, and hoping that they would learn about engineering design as they did it.

All of the groups soon picked some variable that they thought could have an effect on the distance and started to test it systematically to find an optimal value. Throughout, Leslie kept the students in the center. When a student asked her how large the range of testing should be she replied, “That is 100% your decision.” And when she came upon a group making decisions about their design based on visual observations only, she validated their work thus far but pushed the scientific inquiry agenda, saying, “See what you guys are doing right now is what I want you to do, but I want you to do it with *data*” (Leslie’s emphasis). The students responded, “Oohhhhh!” and they started arguing about how to make their design more consistent to reduce the variables changing from trial to trial. Leslie used the word “data” to trigger student’s regular laboratory skills and responsibilities—requiring repeatability, controls, adequate trials, etc. She did not stop their divergent thinking and reasoning; she just needed to remind them to use their laboratory skills to justify their optimization.

When she approached the group that removed the spoon from the initial apparatus to make a long lever arm, she found that they were systematically changing the position of the fulcrum. That seemed adequate for her scientific inquiry needs, and she did not intervene further. In that moment, she decided that even if it felt like they might have been violating some rules from the problem statement, they were still using scientifically sound methodology for data collection. This moment is evidence that even in her discomfort with the arm coming off the device, good scientific processes helped her stay comfortable.

This group's choice to totally change the design was still a uncomfortable enough that Leslie and I discussed it after class. After all, the problem statement said, "Revise this catapult design" instead of, "Demolish and ignore this catapult design." After class, Leslie and I discussed if their design met or violated the design brief.

Leslie: They didn't like that it was attached to the bottom piece. Which is interesting to me because I feel like that just gives so much good control and they were struggling with—it was going kind of wonky. You know, it was kind of [off] in their first experiments. It was not really—they weren't really able to aim it at all.

Katey: Cause like that neck is thinner than like a one inch—

Leslie: Right and he was just like karate chopping the front, you know? And the spoon was flying, and…I don't know.

Katey: Hmm.

Leslie: But it's not like we created any parameters that was like "all your pieces have to stay attached to your catapult."

As we talked further, Leslie pointed out that the design brief did in fact ask the students to make something "reliable," and these students had not. In that way, this case also presented an opportunity for this group and the whole class to learn something about meeting the brief from these students:

> Katey: But maybe that's part of reflecting on the process?
>
> Leslie: Yeah.
>
> Katey: You know? Like, "Were you able to confine your variables to have just one that was changing?"
>
> Leslie: Yeah.
>
> Katey: "And if not, do you think that impacted the reliability of your results?"
>
> Leslie: Mmm, I think that's going to be…a really big point is, "Did you walk in…You should have walked into the competition knowing exactly where you were at. Like with a little bit of you know uncertainty? But you should have pretty much known like this is going to hit if your, if your contraption was made consistently."

By discussing consistency as a class, there would be a chance to get to why the method was incompatible with the aim of the challenge. Students were supposed to be able to make a recommendation to their stakeholders and know the expected outcomes of the design, and then to showcase it at the final competition. However, these students could not know because of the inconsistency of their design.

5.5.1.5 “Finish taking your data, emergency style!”

With time in class running out, Leslie hit a wall of frustration. Her responses became shorter and more direct. When she asked a group, “How’s it going?” and they responded with a casual, “Pretty well,” Leslie shot back. “Are you guys meeting your criteria? [Students: No?] Then is it really going well?” Leslie was losing her cool. As time ticked down she began to panic about the data collection. “Okay, there’s only seven more minutes. You all need to finish taking your data, emergency style.” Leslie’s plan for a complete data set was under threat. She had been relying on her “inquiry avails” resource, especially since she was nervous about them doing the rest of the engineering stuff “right.” So she needed that dataset to validate the work the students just spent a whole day on and would not be able to recreate exactly in the future. If the catapults were dismantled, it was unlikely that they could recreate the exact same materials and conditions when they returned to her class in 48 hours.

Leslie let the students work until the very last minutes of class. Then, in the last three minutes, Leslie called everyone out to the hallway for the first ever Pumpkin Chunkin’ Prototype Competition. The students set up their optimized devices on a line in the floor tiles. Leslie went over the ground rules. “Remember, in order to qualify, success was to get it past point-seven-five meters, which is what this line is here, okay?” She asked the students, standing against the lockers on both sides of the launch site, to be the contest judges and to note where the pumpkins first landed. “You all here are going to be deciding whose [pumpkin] first lands the furthest [away].” Leslie and her students also co-constructed other rules of the game in the moments before the launch.

> Leslie: Question for the group: Does it still count if it hits the wall or one of us and then hits the ground?
>
> Students: No!
>
> Leslie: Okay that will not count. Do they get a redo?
>
> Students: Yes!
>
> Leslie: Okay they get a redo. What if it hits the ceiling, should that count?
>
> Students: Yes!

Finally it was time to chunk the pumpkins. The launch scene was joyous with candy pumpkins flying, kids laughing and arguing about who landed where, pumpkins bouncing off of the ceiling, off lockers, off students, and onto the floor. The winning team was the detached-arm team, and they received clean candy pumpkins to eat or share.

5.5.1.6 Reflections at Lunch

That day at lunch, after facilitating her first section of Pumpkin Chunkin,’ Leslie was very tired. She explained her fatigue was due to stress during the challenge caused by a fear of doing the engineering-design facilitation poorly. She said that it wasn’t a fear of the students not getting it, but it was actually a fear of teaching engineering design wrong, or them doing engineering design wrong that had her stressed out. She was further stressed by my presence because she ascribed me expert status.

Leslie: It just comes down to, again, the fact that I'm like, trying to follow rules trying to, um, present this according to those invisible rules that I just like create in my mind.

Katey: Yeah.

Leslie: And so it's like, "Okay, what vocabulary do I need to use? What is legal? What's illegal when it comes to this project?" And I think that's why it feels so uncomfortable…because there's actually a ton of freedom in this project, and so to me it's like, "Oh my goodness." It is very opposite of what curriculum usually looks like where kids have one little pathway that they can have some wiggle room on but for the most part it's very much um, you kind of are looking for repeated results…

Katey: Mm-hmm [affirmative]

Leslie: …or repeated creations. Very similar creations. And even with [the] roller coaster project like, they come out looking different but they're still very similar like in their, at their core, I would say.

Leslie wanted to teach it "right" or in a way that her engineering coach, or a broader engineering community, would approve of. But she had not yet fully conceptualized the engineering design process, and was feeling insecure. Her only sure markers for correctness were some correct definitions of vocabulary, and so she had tried to make sure they got the vocabulary words defined "correctly" even if it felt stilted or awkward.

And yet, even though she was struggling with getting things “correct” relative to some “right” version of engineering, she got past it to continue in the lesson. She stuck with her lesson plan by calling up her resources of confidence in inquiry, good data, student teams, and knowledge as fabricated stuff. At lunch, Leslie recalled that she had insisted that one student should look to her data for answers instead of the teacher. The group’s data was coming out in a way that the group had not expected, and Leslie took the opportunity to remind them about inquiry skills, not to lead them to an answer. Leslie recalled the interaction after class: The student approached Leslie and said, “Miss. Knope, my last data point is lower than the one before it, but it’s supposed to be linear.” Leslie remembered her response, “I was like, ‘Maybe not. Maybe there’s a point where it changes and you just need to go with your data tells you.’ And [the student] was like, ‘What.’ And I was like, ‘Go!’ We didn’t talk about peaking!” Leslie recalled this interaction with a smile. Even when the new engineering material caused her insecurity, Leslie was confident with the inquiry embedded in the engineering-design lesson because she was comfortable with requiring that students reason through their own data. Leslie concluded, “I just am excited for them to see meaning in their data.” Clearly, Leslie felt engineering design had provided that opportunity, at least in the one case.

In the next class, Leslie began to enjoy the chaos a bit more, and after school she scoffed in amazement at a student in 7th-period who said, “I don’t want to be creative; I just want rules.” Leslie was beginning to enjoy the lawless world of divergent thinking, and she was beginning to note when others did not.

After lunch, Leslie and I rebuilt all of the catapults to be like the original model, so that a class set matching the lab handout was ready to go again. Leslie microwaved some water for tea and made sure she had 7th-period's quizzes ready to pass back. As students trickled in and noticed the board, "Ms. Knope, what's the catapult project?" Setting the context anew, Leslie's energy returned. In her purring, intense, ghost-story whisper she told them, "All you need today is a pencil and a brain" and the challenge began again.

5.5.1.7 Summary: What productive resources got Leslie through this?

Leslie ran into a tension between a concrete understanding of what's acceptable for engineering-design instruction and how she normally expected her students to learn—constructively, collaboratively, and exploratory. This tension made her feel stress and exhaustion, feelings that could have made her give up on the challenge, abandon the open-endedness of it, or not do it again. But she made it through and did the Pumpkin Chunkin' Challenge again, and again as she originally planned.

Coherence of resources did play a role, although this paper really identifies resources individually more than as units. I saw evidence of Leslie not giving away the steps combined with the constructivist views about how students' physics knowledge is socially constructed and combined with a belief that student struggle is productive for learning. For example, in the Pumpkin Chunkin' warm-up, Leslie listened closely to students working and answered their questions with her own questions. When one group asked her about acceleration, she said, "I'm hearing ‘constant velocity,’ so what would acceleration be?” When that did not help them think about acceleration she said, “What is the *value* of your acceleration if you’re moving with a constant velocity?” (Leslie’s emphasis). These moves were her attempts to guide students without restating relationships that the students should recall on their own. Leslie also reminded them that this material was on their last test, prompting students to take out their old notes instead of giving them answers.

At this point in her own understanding of engineering design, Leslie believed there was a right way to do engineering and feared teaching the students a wrong way. But when teaching, several resources came together, as they did when she was teaching physics, to help Leslie continue her engineering-design instruction in a constructivist way, instead of removing student agency or saying “this is engineering design and here is how to solve your problem.” Some of the spirit of “spaghetti on fire” came out in the divergent moments of the lesson, and Leslie held on by reemphasizing the context, the data, and the importance of group consensus. Students thought far and wide, and Leslie encouraged them without giving away what she might prefer or think was correct.

At lunch, Leslie also told me about one group’s data that was really poor because they were changing multiple variables. She drew their attention to the fact that their data wasn’t showing the progress of one variable changing:

> Katey: I got that back [group], their whole thing on tape basically. It will be interesting to see, like you went over there and you were like, “So, you’re changing things as you go?” and they were like, “What?”

Leslie: But I think they were kind of mad because their data was crap.

Katey: The data was crap?

Leslie: The data was showing, the data was showing them that they had no clue as to what was happening. But then they got it going pretty well.

Katey: The data was showing them failing, that's what was upsetting them.

Leslie recalled how she identified and pointed out bad data, and how after that experience the students had started taking better data and finding useful information in which to ground their conclusions.

This episode points to Leslie drawing upon a learning-from-failure resource, and how any co-constructed knowledge about hands-on activity is probably moving towards learning something in science. Leslie recalled that students were able to continue in the process, and their learning from failure encouraged her reciprocally.

Leslie had asked students to build a fictitious context around an inquiry problem, picking their own hypothetical role, criteria, and stakeholders in the refined problem statements and then completing an inquiry experiment to find best conditions. Leslie was able to lean on her cognitive resources for quantifying variables, taking good data, and doing repeated trials when she became unsure about whether the students' engineering designs were appropriate or not. She did not give away "correct" answers, and she did not tell them what to do. She used her well-practiced open-ended-inquiry-facilitator skills to push the inquiry agenda forward even though the engineering process was stressful.

Comfort with open-ended inquiry facilitation was especially productive for Leslie's engineering-design instruction. The data was still paramount for Leslie, even when wide design divergence was occurring. When the validity of the data came into conflict with divergent thinking—e.g., students were changing so many things rapidly that they could not assign outcomes to any specific variable—Leslie used subtle facilitation moves to get the students back to, at the very least, collecting good data to justify their conclusions.

Although she expressed concern about the Pumpkin Chunkin' Challenge not being "right," after seeing the issues resolve themselves, students collect and analyze data, and pumpkins flying to meet both constraints and criteria, she was fine. And after she got into it, the fun did not stop. "It was so fun. It was just so fun for me. Right? By the time you get to this kind of teaching it's like it's for the kids, but, also, I need to be entertained, right?" The personal entertainment that Leslie got out of this lesson helped her succeed as she tussled with her own doubt.

5.5.2 Discussion

Leslie's open-inquiry constructivist mindset and facilitation skills, as well as the resources associated with them, came back repeatedly to assist her in engineering-design facilitation and put her back on "safe ground" even when it felt like the lesson was shifting into total chaos. For instance, when she was worried about data collection skills in the Parachute Challenge, she relied on a well-designed technical resource sheet to stay agile in the lab space. When students wanted to improve the catapult by changing its color, she insisted they use good data to justify their design decisions. She taught productive failure by testing iPhone cases to failure, and then creating a second and third iteration.

The association between open inquiry and engineering design seems especially provocative to me as a teacher educator and professional support provider of mathematics and science teachers. Leslie's case seems to suggest that teachers might find engineering-design integration is easier to implement when they call upon with open-inquiry facilitation skills and resources associated with open-inquiry facilitation.

That scientific-inquiry resources may be called upon to assist teachers confronting the challenge of bringing engineering design into their classrooms is important. Leslie did not need a new set of resources to start doing engineering design. In fact, it can be argued that she began her instruction of engineering design with a huge misunderstanding about it; she thought there were wrong and right ways to design, and that there were limits to the options that could be explored apart from the problem's scope. Leslie was still developing her understandings of engineering design, but she was simultaneously able to help students complete the divergent activity for which she had planned.

It is significant that Leslie did not give up designing her own engineering design challenges. Many teachers might not spend the time on designing challenges or trust that they have the authority to know if a project is "good." Clearly, Leslie faced this fear with her "Am I doing this right?"-type concerns. In this case, Leslie had someone, me, nearby to assure her she was fine, and my kind of leadership and observation in this study were such that, in the moment, I wanted to watch her actions, not manipulate her. So I assured her that it was okay. If other teachers need an “expert” to help their confidence and engineering-design authenticity, whom will they turn to? It is little wonder that pre-packaged curricula are the current normal for K-12 engineering instruction—the authority of the curriculum may assuage teachers’ fears that they are facilitating engineering incorrectly.

The results of this study are crucially dependent on Leslie’s context in Merlin High School. The supportive climate of Merlin and the lack of standardized test mandates allowed Leslie to try new practices and to focus less on specific content standards. Other teachers have to confront standardized tests and burdensome regulation even as they teach their basic subject matter. Those teachers might not be allowed or feel confident enough to try seemingly risky engineering curriculum. Because of these factors, my results cannot be overly generalized to other teachers in every other context. However, it is worth looking at Leslie’s resources as a best-case scenario; where more pressure exists, drawing on productive resources will surely be more difficult.

5.5.3 Epilogue

After this initial foray into engineering design planning and instruction, Leslie went on to design and teach four more engineering design challenges—a Parachute Challenge to teach terminal velocity concepts, an iPhone Drop Challenge to teach impulse and momentum, a Roller Coaster Challenge to demonstrate work, power, energy and efficiency, and a Musical Instruments Challenge to demonstrate wave properties and harmonics. In each subsequent engineering design challenge, she continued to draw upon the resources outlined here. For instance, she continued to try to position the student designers, their peers, and the results of their own experiments as more authoritative than her. She insisted that students use data to support their conclusions, whether in engineering challenges or in non-engineering physics instruction. In each engineering challenge, Leslie used creative contexts to motivate students' designs, such as needing to protect an iPhone or becoming America's next top rock band. Leslie also became much less concerned with getting engineering "right." At the end of the year, she said that she now believed engineering was not just one specific process, but some amalgamation of iterative problem strategizing and solving.

Leslie grew to appreciate various aspects of the engineering design process in more sophisticated ways, though I am not analyzing them or passing judgment on them here. For instance, she came to see iteration as a significant difference between engineering design and scientific inquiry, and began to miss the presence of iteration when any non-engineering lab she instructed had only one opportunity to take data on a phenomenon. She said that if students could see a trend or pattern, then they should be able to manipulate the situation so that they could predict another trend or pattern, take the data a second time, and confirm their conclusions, instead of having the teacher do it.

Around February, Leslie became interested in talking to teachers about engineering-design integration. What started as an idea for a county-wide in-service, blossomed to her involvement as a facilitator-in-training at a week-long engineering design-integration summer workshop for high-school mathematics and science teachers. Leslie changed jobs at the end of the school year. She became a STEM coach for a district, and began to advise K-12 teachers on engineering integration. She said that her experiences learning about, thinking about, and ultimately teaching engineering integration gave her motivation and confidence that she could help other teachers use engineering design in their classes.

5.6 Conclusions and Future Directions

High-school physics is considered a "prime target" for engineering-design integration, offering a "relatively mild transition" for teachers (Dare et al., 2014). But even the best-intentioned physics teacher may face difficulty trying to bring authentic engineering design practices and problems into a physics class in a way that also provides inquiry opportunities and contextual engagement for student buy-in.

In this study, Leslie confronted classroom chaos, time restrictions, and divergent student actions in her very first attempt at planning and teaching engineering design. The productive resources that Leslie called upon to get over these difficulties related to her open-inquiry-instruction facilitation skills and general constructivist attributes of student authority, a trust in empirical data, and a growth mindset. Her brand of engineering-design instruction, with embedded content physics, offers one illustration of how to implement the NGSS for high-school science instruction.

Leslie’s interest in “fun” for herself personally aligns with other research on “enjoyment” (Dare et al., 2014), but in the other research, teachers reflected on student enjoyment, not teacher enjoyment. Further research could investigate the personal enjoyment that teachers experience and examine the emotional resources that are triggered when teachers themselves enjoy an activity, like Leslie said she did here. Other emotional resources like trust, fear, stress, and excitement could additionally be investigated for the role that they played in Leslie’s instruction.

This paper also opens a discussion about whether Leslie’s resources would be recurrent or cohesive in any other settings, and how those formations and activations would change over time. Further investigation of Leslie’s use of engineering design over the whole school year could begin to describe how her whole first year of engineering integration looked, not just her first try at engineering. Such research might be instructive for coaching science teachers as they integrate engineering and would be of particular interest to me as I progress in my career.

Chapter 6: Summary and Future Directions

Engineering design is a problem-solving practice that could help U.S. students immediately and help our country in the future (Lander & Gates, 2010). Teaching engineering design to K-12 students while simultaneously teaching them science content is a new endeavor. This will require teachers to understand engineering design (Katehi et al., 2009) and try some new teaching practices. This dissertation identified some of the tensions that three physics teachers experienced during engineering-design integration, and also some resources that teachers called upon during tense moments.

This dissertation analyzed three tensions that emerged when a team of teachers taught terminal velocity using an engineering-design challenge. Each tension involved differences between (a) instructional moves that any well-intentioned teacher might use to try to make help students learn better and (b) how such moves may be in direct conflict with engineering design. These analyses showed that pedagogical moves that are productive at other times in other scenarios, may conflict with the integrated vision of engineering design in NGSS.

This dissertation then identified some of teacher Leslie's inquiry-based instructional resources and found that some resources helped when she tried engineering-design instruction for the first time, particularly resources that related to inquiry facilitation in physics.

6.1 Implications

This study has shown that engineering-design integration isn't simple—it's complex and fraught with tensions. Teachers trying it can struggle with internal conflicts when their usually supportive teaching moves prove to be counter-productive and undo the intended outcomes of engineering design. Hopefully, identifying some tensions that these teachers felt and understanding resources that Leslie called upon might allow researchers, teacher educators, and professional growth facilitators to better support, encourage, and assist teachers to negotiate difficult challenges in engineering-design integration and teaching reform more generally. The utility of Leslie's inquiry-facilitation resources for engineering-design instruction could provide a guide for how to facilitate engineering design but also how to draw upon teacher's existing resources for this new engineering instruction work.

K-12 science teachers should be encouraged to read about what is different in engineering-design instruction and reflect upon how the differences align with their pre-existing values for student learning. Teachers should explore and enumerate what works for their regular instruction and what keeps them and their students feeling safe. Identifying the ways in which their safety practices and resources relate to the risky foundations of engineering design might help teachers to stay on message during instruction and do more authentic engineering design with their students.

Teacher educators should discuss tensions and resources with their teacher-students and provide opportunities for them to attempt instruction in a low-risk environment such as peer teaching. The discussion should address the fundamental nature of engineering in depth and draw comparisons to the nature of science. This may help to make sense of what engineering design is trying to accomplish and how engineering-design facilitation is different from "regular" supported instruction.

Reform-oriented engineering-integrationists need to achieve clarification or consensus concerning the level of authenticity (real-world engineering experiences) desired for K-12 engineering-design integration. What should the range of experiences be? What are some acceptable minimums for teacher and student decision-making and authority in the integration that is envisioned? The relative complexity of engineering design, combined with the constraints of the classroom, may lead to inauthentic experiences, perhaps more closely aligned to what Chandler, Fontenot and Tate (2002) called "preengineering" (p. 40). If reformers want more professional-looking engineering instead, then more guidance on minimums must be provided.

6.2 Future Directions With the Merlin Data

This dissertation includes only a small subset of the stories and arguments worthy of telling from the study's observations and experiences at Merlin. Analyzing the data and writing this dissertation caused the author to begin thinking about future research directions. The following are a few ideas for how to re-interrogate the Merlin dataset in the future.

6.2.1 Participant Observation as Professional Development

This dissertation does not investigate the use and the potential of the PD model employed in the Merlin study. This study suggests that PO can be involved in PD by meeting various hallmarks of "high-quality PD," such as significant duration, collective participation from a local group, and content-focused collaboration around a set of reform standards (Desimone et al., 2002; Lieberman, 1995; Supovitz & Turner, 2000) that helped the Merlin teachers implement reform in their classes.

Interrogating the dataset to identify which features of the PO were most significant for teacher change, and what function they served, could help to inform future teacher-researcher collaborations and potentially change the one-shot workshop models of PD that research has shown are not deeply meaningful (Goldenberg & Gallimore, 1991). Some features of this PO-PD hybrid are (1) the PI drew on teachers' prior knowledge and motivations, (2) goals and agendas for the PO were flexible and responsive to teacher needs, (3) logistical aspects including time, space, and virtual elements (including online planning meetings with food sent by the PI to the teachers at school, a.k.a. "virtual pizzas," online interviews, and online member checks) accommodated both the teachers' and the PI's time and locations, and (4) the research acknowledged and accepted real-life issues.

6.2.2 Study Collaborative Norms for Productive Contribution

This study was not about the team collaboration; however, the support that the Merlin teachers offered one another was highly productive if not instrumental in their beginning engineering-design instruction. In the future, the author would like to study the ways that the collaborative group collectively supported change in teaching practices, and how the individuals expressed and negotiated epistemic differences within the group. This might include finding out whether epistemic alignment was a prerequisite for instructional agreement or what roles the teachers' epistemologies played in deciding group goals and instruction.

6.2.3 Study Persistence of Tensions

This dissertation also does not describe the interplay of engineering and science over time. The teachers' developing relationships between engineering and science could be followed throughout the remainder of one, two, or several school years. Some work like this was done with a pre-episode for Leslie in Chapter 5, but much more could be done.

The sample of teachers' individual responses to various tensions in Chapter 4 may or may not prove to be indicative of common stances that teachers have across the sciences. Using the priorities identified here, researchers could extend this line of questioning to other science teachers to seek a more expansive theory of engineering integration tensions and successes.

6.2.4 Study Student Outcomes

Clearly, researchers and teachers would like to know about student outcomes in terms of engineering-design understanding and content physics learning. This study did not address student outcomes, but future research should. Student conceptual change about engineering design and about the content goals of the lesson should be studied.

Excitingly, the three Merlin teachers were closely monitoring their student outcomes including student engineering-design conceptions. Katniss even organized a study to compare her students' conceptions of engineering design to those of students in an engineering or technology course, and Leslie gathered student conception data. These teachers' action research and inquiry into their practice was encouraging to see and deserves study. For example, what elements of student learning do teachers value and track throughout early and later engineering integration?

6.3 Future Directions Outside of Merlin Data

The author's future research interests outside of the Merlin dataset involve PD and engineering-integration tools. Publishing lesson-planning tools and PD tools for teachers, teacher-developers and curriculum/reform-writers could increase engineering-design implementation in high-school science.

6.3.1 Teacher Change Through Efficient Instruction Goals

Although this dissertation does not discuss it fully, it seems from this study that teachers' instructional decisions are driven by efficiency towards meeting their instructional goals. Perhaps teacher change can better occur if teachers reorient their goals and then work towards teaching efficiently again. Without changing goals, any changes in instruction could be perceived as less efficient ways to reach a former goal, and will thus be rejected.

The author is interested in studying the way this theory plays out in various contexts including engineering-design integration (such as what teacher Leslie is doing now, and the author's work with other teacher groups including KSTF's Lever Engineering Group), but also beyond engineering-design integration to include other systemic teaching reform agendas (e.g., student-centered teaching in college astronomy, reform and critical teaching in mathematics, equity in writing conferences, and student-centeredness in undergraduate lab assistant practices.)

6.3.2 Levels of Inquiry and "Levels" of Engineering Design

One emergent direction from this dissertation is a model for "levels" of engineering-design instruction. The open-endedness of engineering design may be compared to visions of inquiry in the National Science Education Standards (National Research Council, 1996). By mapping various amounts of teacher guidance during engineering design challenges, more or less teacher and student authority may be scaffolded. My "Levels of engineering-design instruction" model (Figure 6.2) is based on a four-level model of inquiry instruction (Bell et al., 2005) (Figure 6.1). To help teachers use inquiry in their teaching, researchers identified levels of support to scaffold students' independent thinking and experimentation. These four levels of inquiry provide a guide for teachers conceptualizing and instructing scientific inquiry.

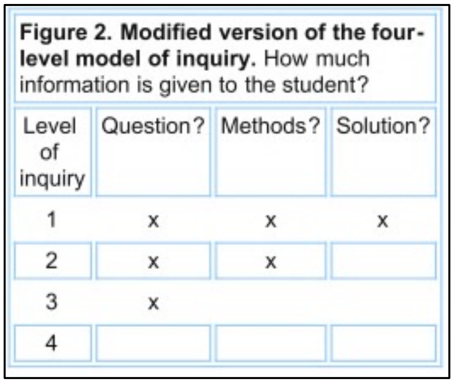


Figure 2. Modified version of the four-level model of inquiry. How much information is given to the student?

Level of inquiry	Question?	Methods?	Solution?
1	x	x	x
2	x	x	
3	x		
4			

Figure 6.1 [also 2.5] Levels of Inquiry (Bell et al., 2005, p. 32)

Analogously, there could be levels of openness in engineering design. For example, say that "open" engineering design is where the student finds and defines the problem, brainstorms design ideas, and decides on or develops how to evaluate the design. Other kinds of engineering, like engineering sciences coursework, could then simply be thought of as lower "levels" of design openness—design where the problem is defined, the tests predetermined, or the solution provided. For instance, "Find the tensile strength of this structural member. The book says it is 50 Newtons per square meter," would be Level 1 or "confirmation engineering design." Level 2 engineering design or "structured engineering design" would mean that the design is not given but the problem is defined and the tests are given, such as, "Design a solution to raise this mailbox to a height of 70 centimeters." Level 3 engineering design or "guided engineering design" would offer a defined problem such as, "The boatyard needs a way to more efficiently evaluate the contents of shipping containers at a rate of 20 per hour minimum." Level 4 engineering design or "open engineering design" would be more like a suggestion of a problem without providing a problem scope. For instance, “Develop a problem and design a solution for food waste” might be an open engineering design prompt. In Level 4, the student would need to settle a range of problem definition concerns that a client in a real engineering job would provide by asking, “For whom? Where? Why?”

An initial framework for this scaffolding, shown in Figure 6.2, substitutes “challenge definition” for “scientific question,” “data collection or research methods” for “procedures,” and “evaluation of design” for “conclusions.”

Level of engineering design	Challenge definition (context, criteria, constraints, materials)? [In inquiry version: Question?]	Data collection or research methods? [Procedures?]	Evaluation of design? [Conclusions?]
1	X	X	X
2	X	X	
3	X (some or all)		
4			

Figure 6.2 Levels of Engineering-Design Instruction Mapped Onto Levels of Inquiry

It would be interesting to analyze recommendations for engineering-design instruction and teacher use to see whether the analogy of levels of engineering holds in various engineering design challenges. Additionally, this model could be used in PD with teachers to see if they would find it helpful for conceptualizing engineering-design instruction. Perhaps they might; the idea of scaffolding inquiry is already established for many science teachers.

6.3.3 A "Nature of Engineering" is Needed

Inquiry-like levels are not the only holdovers from pre-NGSS science that the author hopes to explore in the future; the nature of science translated to nature of engineering is another. NGSS Appendix D (NGSS Lead States, 2013a) nods to how the NGSS's inclusion of engineering will create epistemic and history of science dissonance by changing which historical societies and individuals are recognized for their contributions, but it stops short of acknowledging that teachers might have epistemic dissonance around engineering design use as it relates to content.

Although this dissertation study did not investigate the nature of engineering stances of these teachers, it did illuminate a need for investigation of how teachers understand the balance of engineering-design instruction and science content instruction, and how educators can shift to a more unified perspective, if at all. This study did not delve into the Merlin teachers' epistemologies of engineering and physics, but future research could interrogate the Merlin dataset to try to understand, through an epistemic lens, how the teachers envisioned the relationships between engineering and physics and seek ways that those epistemic stances influenced engineering design prioritization.

Recommendations for engineering reform idealize students as acting like semi-professional engineers handling real-world engineering challenges (Katehi et al., 2009) but it is more likely that engineering instruction in high school is necessarily reduced in level of difficulty in the same manners as other sciences. Engineering design in a high-school classroom can only be an approximation of real-world engineering design. Even stand-alone high-school engineering courses can only approximate the complex, market-driven, technology-centric engineering profession. A meta-perspective is needed to remember that there is more to engineering design than can be modeled and conducted in a well-resourced typical high school, never mind in a less well-funded or understaffed school.

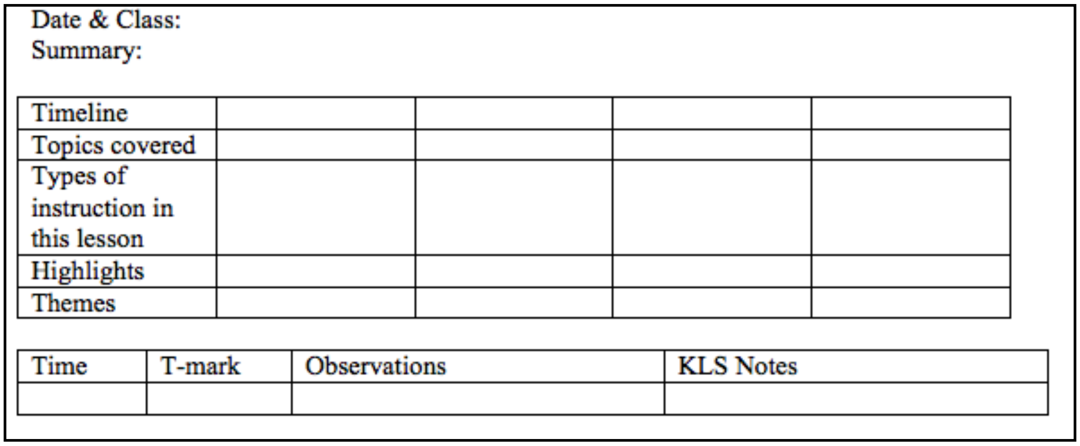
Instead of demanding that science teachers capture professional engineering in its entirety, perhaps another approach could be used. Students could learn the limitations of classroom engineering and engineering design in some "Nature of Engineering" terms. Just as the Nature of Science (NOS) movement makes clear that classroom inquiry is only an approximation of professional science, by highlighting the limitations of classroom inquiry, a similar Nature of Engineering (NOE) understanding could be established and used in conjunction with engineering-design instruction to make the limitations of classroom engineering clear.

Similar to the NOS tenet "Science is a human endeavor," engineering educators know that "engineering is a human endeavor and thus it is subject to error" (Petroski, 1992, p. 2). Teacher educators would be wise to keep this in mind and make sure that science teachers understand it. Not only could this honesty around what engineers do provide a more authentic education, it could perhaps also decrease teacher intimidation when trying engineering design. Perhaps just as science education reformers now suggest the NOS should be instructed carefully and deliberately, so too might engineering-design education reformers recommend the NOE be taught explicitly.

Research has shown that teachers' misconceptions about the NOS can negatively impact the depth of understanding about science that students can perceive (McComas et al., 1998). Research is needed to determine whether teachers' misconceptions about the NOE have a similar negative impact on students' conceptions of engineering design. In summary, the NOE needs to be better specified for teachers, teacher educators, and curriculum developers, and teacher and student conceptions of the NOE as well as NOE impacts on student learning, require study.

Appendices

Appendix 3.1: Observation Template v4



Date & Class:
Summary:

Timeline				
Topics covered				
Types of instruction in this lesson				
Highlights				
Themes				

Time	T-mark	Observations	KLS Notes

[Additional rows are added when tab is pressed from the lowest right-hand cell.]

Appendix 3.2: Intervention Methods

After initial observations, we had a formal planning session on October 5th to begin discussions about engineering-design integration in their classes. To help the teachers learn about engineering design I invited them to actively and experientially construct a preliminary understanding of the engineering design process: as a team they worked through an engineering design challenge (design a tower to help a garden gnome escape a post hole). The point of doing the challenge was to give them some experience with engineering design that was on the scope of a high-school class activity and to present some potential scaffolds and frames for getting into engineering design in class.

Then the teachers reflected individually and discussed collectively how to describe and diagram the process they went through. After they reached a comfortable consensus, I then showed them two alternative models, the NGSS three-part model (Figure 2.3) and the four-phase engineering design diagram (Figure 2.4). As a group we discussed the differences, affordances and drawbacks in each of the three models and how the practices of engineering (NGSS lead states, 2013) mapped onto any and each of them. The teachers were invited to iterate their model if they wanted to. This exercise was intended to help the teachers see that the models as just that, visual simplifications of the engineering design process.

After the first meeting, my interventions were less didactic. For the remainder of the school year I assisted them individually or as a group when they planned engineering (and frequently when they planned physics). At one afterschool meeting per month I brought food and it felt slightly more formal, but we met frequently at lunch, or during a planning period. Often I would bring in a graphic organizer, examples of engineering project ideas, or another teacher's engineering design student work that I felt would be useful to our planning process, but I did not create agendas or PowerPoint presentations for the planning meetings after October 5th. I just tried as much as possible to be a helpful colleague with some engineering design experience and physics expertise to share.

This study does not analyze the success of the professional development or planning sessions, or even describe this model of professional learning fully, but the study met many hallmarks of high-quality professional development: it was sustained, it was supported by department and administrative support in the local context, it involved local, content-coherent planning group, focused on content matter, involved active engagement, and reflection.

Appendix 3.3: Table of Whole Year Timeline

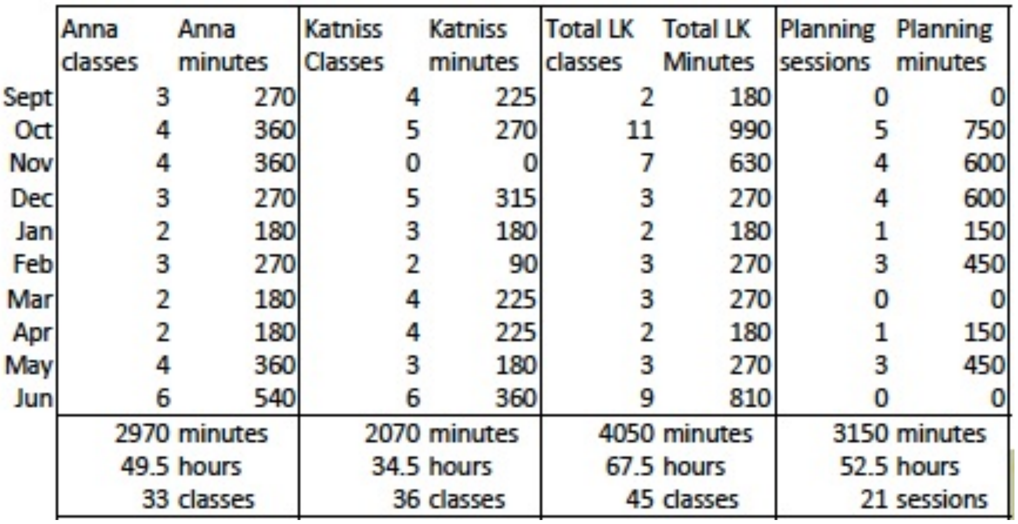
May 2015	· Initial contact made at Merlin and Merlin's district
June 2015	• Formal submission to district for study approval • UMD IRB Approved
July 2015	• District and school approve study • Principal approval letter to IRB as amendment
September 2015	• Student form distribution and collection at Merlin commences on the second day of school. • 9 days of observation/form collection at Merlin (9 classes observed) • First interviews conducted CONTENT: Nature of Science activities, group norm setting, patterns labs OF NOTE: • Katniss: Risk-taking mindset • Anna says, "engineer a candy hammock" during patterns spring lab, • Katey: familiarity memo
October 2015	• Two planning sessions (David el Gnomo 10/5/15—intro to eng, NGSS, slices, diamond diagram; Split track with Eagle 10/23/15) • 8 days of observation/collaboration at Merlin (20 classes observed, 5 planning sessions) • Katey: Shifting role—discussion of subbing, resource during class CONTENT: End of patterns labs, kinematics by graphing, buggy lab, flat track lab, planning with Eagle OF NOTE: • Context is key in planning session • Katniss diverge-converge comments in planning session (10/9/15) • Leslie: "IB brain" coined, wants to submit to Samsung STEM contest. • Katniss: If the line didn't go through 0,0 "I could go back and revise the procedure" (10/15/15)(First adoption?)

	• Anna: resists observation/PD (memo) and cell phone “shake up”
November 2015	• 5 observation/collaboration days at Merlin (11 classes observed, 4 planning sessions) • Leslie second interview (11/30/16) CONTENT: kinematics, acceleration, free fall, forces OF NOTE: • Leslie plans Pumpkin Chunkin’ Challenge (11/4/15), LK (11/23/15) and Anna try it, I teach it once (11/24/15) • Leslie says they’re thinking of planning coffee filter lab as an engineering goal (11/18/15) • Katniss plans an engineering challenge for her IB collaboration (11/30/15)
December 2015	• 7 observation/collaboration days at Merlin (11 classes observed, 4 planning sessions) • Anna 2nd interview CONTENT: Free fall (Parachute Challenge), forces, Newton’s Laws, planning OF NOTE: • Parachute Challenge free fall lab planned and executed by all three (12/8/15 to 12/18/15) • Anna super frustrated • Breakthrough memo: Open inquiry relates closely to eng. design instruction
January 2016	• 4 observation/collaboration days at Merlin (7 classes observed, 1 planning session) • Katniss 2nd interview (remote?) CONTENT: Newton’s Laws, Unbalanced forces OF NOTE: • iPhone Drop Challenge planning • Three different ways to handle the problem with the car lab (1/13/16) • Planning iPhone Drop Challenge over “virtual pizza”, interview over Skype: collaboration

February 2016	• 4 observation/collaboration days at Merlin (9 classes observed, 3 planning sessions) • Leslie 3rd interview CONTENT: Energy, Impulse/momentum OF NOTE: • iPhone Drop Challenge executed • Bad and sad days at Merlin, Kate out, Kate sick, family loss
March 2016	• 5 observation/collaboration days at Merlin (some remote) (8 classes observed) • Katniss, Anna 3rd interviews CONTENT: Impulse/momentum OF NOTE: • End of iPhone Drop Challenge
April 2016	• 5 observation/collaboration days at Merlin (8 classes observed, 1 planning session) CONTENT: Energy, work, power OF NOTE: • Rollercoaster project (no iteration)
May 2016	• 5 observation/collaboration days at Merlin (10 classes observed, 3 planning sessions) CONTENT: Waves, sound OF NOTE: • Music Instrument Challenge planning/starting
June 2016	• 10 observation/collaboration days at Merlin (21 classes observed) • Last interviews conducted

	CONTENT: Waves/sound OF NOTE: • Musical Instrument Challenge work and performances • End of year pack up and leave

Appendix 3.4: Total Observation and Planning Minutes



	Anna classes	Anna minutes	Katniss Classes	Katniss minutes	Total LK classes	Total LK Minutes	Planning sessions	Planning minutes
Sept	3	270	4	225	2	180	0	0
Oct	4	360	5	270	11	990	5	750
Nov	4	360	0	0	7	630	4	600
Dec	3	270	5	315	3	270	4	600
Jan	2	180	3	180	2	180	1	150
Feb	3	270	2	90	3	270	3	450
Mar	2	180	4	225	3	270	0	0
Apr	2	180	4	225	2	180	1	150
May	4	360	3	180	3	270	3	450
Jun	6	540	6	360	9	810	0	0
	2970 minutes 49.5 hours 33 classes		2070 minutes 34.5 hours 36 classes		4050 minutes 67.5 hours 45 classes		3150 minutes 52.5 hours 21 sessions	

Appendix 3.5: Longer Narrative of the Year

Initial Observations

The physics curriculum that the team teaches follows a fairly traditional sequence; mechanics and dynamics take up most of the Fall and blend into the spring. Students do some electricity and magnetism before waves. But at the very beginning of the year they do a NOS unit to teach students what the scope and limits of science and inquiry are, and, as Katniss said, to "build norms" in the classroom. I saw the teachers focusing on collaboration, teamwork, justification from evidence, observation versus inference and the tentative Nature of Science.

I observed Leslie Knope conduct a "Mystery Cube" NOS activity where she asked each "table" (set of four desks) to pretend to be a country, and collaborate on space explorations to understand a cubic celestial object that they could only observe five sides of. "Here we have the world wide scientific community: Japan, the Mediterranean, Canada, [Merlin]." Anna and I worked out her comfort with me in her room over the first several weeks of school. She asked me not to come in until she had "found her groove" with her classes. In the early weeks of school Anna was taking time to get to know her students well so that she could place them into groups for the entire year.

The NOS unit flowed directly into a "Patterns Unit." As Leslie told her 6th period on September 16, "We all saw the same things, observed the same things, but not all of us had the same inferences. We're going to build on all of these by talking about seeing patterns in our world and making predictions based on those patterns.” In the patterns unit, students worked within a scientific process to collect data, graph it, and make sense of the relationship found in the graph. The students explored four common functions through one-day labs: flat line (y=constant function through a lab where, linear, quadratic and inverse (paragraph width versus height for the same passage).

Initial Glimmers of Engineering Design

I noticed elements of their instruction in the first two weeks that I identified as engineering-like or engineering related. On several occasions the teachers used the words “engineer,” “build,” or “design” as instructions, but rarely did their use of these words align with a process that I would identify as full engineering design. As mentioned in the literature review, I think beginning-level engineering design in high school should involve cyclical and non-linear movement through problem definition, design exploration, design optimization and design communication/justification phases. When Anna told her students to “engineer a candy hammock” to use in their pattern-seeking Hooke’s Law lab (mass versus spring displacement), she wasn’t expecting them to work towards some best candy hammock based on testing and performance, she just wanted them to hang a cup from a spring with a paperclip, but she didn’t want to provide instructions, she wanted them to solve a practical problem with available materials quickly and individually.

All three teachers asked their students to “build” the tallest tower possible out of a single sheet of newspaper and cited “designing” a roller coaster as a way that they incorporate engineering into physics. Building a tower or a bridge is commonly seen as connected to engineering in science class. But the tower and the roller coaster at Merlin were built once without testing, systematic modifications or iteration. These teachers may have realized that they weren’t doing the full engineering design process in during these projects, or they might have wondered what they were missing. Maybe that’s why they invited me to work with them towards a more complete or authentic understanding of engineering design.

None of the teachers identified themselves as engineers directly, but in each of them I saw some elements of systematic problem solving and making products. Leslie fixes and refurbishes furniture for fun in her spare time, but she did not see that as related to engineering. Katniss helps design parkour obstacles for a local gym and organizes a women’s parkour meet up group. And all three of them iterate their curricula based on student data tweaking or overhauling plans as their expectations and classes changed, studying the results with multiple planning teams, and then cycling back to adjust again.

Katniss who called herself “risk averse” identified one student goal that I found pertinent in later discussions about engineering—she wanted her students to be risk takers. In September she said,

> Katniss: I’m focusing particularly on risk taking. I feel like students won’t put ideas that they’re not sure about out there. That’s a really key skill to

> be successful in life. Not just physics. I'm really trying to think about how I can talk about risk taking in a meaningful way or design activities to encourage risk taking and have it be okay now when it's not super risky so that later when we're learning physics content and they're really not sure and just a little scared of physics, that they're still able to take those risks.

Katniss was working on ways to integrate risk taking subtly and overtly in class to build student self- and group reliability, shifting the weight of decision making from herself to her students.

The First Planning Session

My plan for the first session on October 5th was that I would have the teachers would engage in an engineering design challenge that I based on their own spaghetti tower project to "experientially discover and define the engineering design process." After doing this activity, I intended for them to list the steps they used in the process, to help them to relate their actions directly to the engineering design process as I understood it. Drawing parallels to the challenge they did, we would also discuss the handout they received and the facilitation moves used. I brought gifts to the school that day; Thai food, a copy of the NGSS and appendices for each teacher, and a classroom poster of a version of the engineering design process.

I designed the challenge they would engage in, helping a "tiny creature" out of a jam by building a tower out of uncooked spaghetti "straw," to apply context to the team building challenge I observed in their classes during the first weeks of school. The teachers had all eight of their physics classes split up into teams of two to four to build newspaper towers, with the highest one in 5 to 10 minutes winning. So I altered the newspaper tower they used for team building, in an effort to present one of their own activities to them as an engineering project for them to engage in as students. When the teachers led their tower building project in the first weeks of school, their goal was to work on team relationships, not to teach specific physics content or to teach the "engineering design process" more broadly.

I introduced the challenge and gave them a Problem Definition Worksheet: You will help a tiny creature (either a real one like a mouse or a fictitious one like a cartoon character) to escape from a hole by building a tower. The teachers decided their tiny creature would be David el Gnomo, a TV classic. The teachers listened as I described criteria and constraint, but I did not supply them with the criteria and constraints for this challenge. "Criteria are things that should or could do and it should be things that you can improve, like it could be more or less towards doing that. Constraints like 'it absolutely must do that' either based on the [finger quotes] real world which we're suspending a little bit but just put yourself in the world of your cartoon or your movie, and by the constraints of the experience which are the materials available."

The teachers considered the materials available to them: "straw" a.k.a. spaghetti sticks, and other people food including snacks and candy, in light of the mass, height, reach and jump that they estimated for David el Gnomo. They decided to make a massively strong tower, as strong as possible so the tower could be reusable by other gnomes, and set out testing three kinds of joinery; gumdrops, marshmallows, and gummy bears. After collecting data on their materials they decided gumdrops was the way to go and then turned to investigate shapes of tower, ramps, and other ladders.

After defining the problem and doing some initial materials testing, the teachers came together to report on their initial designs and their next steps, which led to another discussion about testing to failure and optimization. Katniss asked, “How do you get them to gather data that really justifies their decisions later?” In her experiences, she said, the students are more or less doing trial and error, so what do you say to them to get them to gather quantitative data? I explained that in the David case, testing to failure would help because then they’d need to make adjustments and try again. In the classroom version (building the tallest tower) I’d need to see more tries, with one thing changing, and measuring for higher heights.

Then we debriefed the activity and generally shared concerns and ideas about engineering design in the physics classroom. The teachers were concerned that they weren’t learning the vocabulary of engineering design adequately: what is the correct definition of constraint? How is it different from criteria? I stated my definitions of criteria and constraint again and the teachers nodded, but no one restated the definitions in their own words.

They were also very concerned about using engineering design if it wasn’t going to teach content, or worse, if it was going to confuse what the emphasis of a lesson was. They asked, How can doing a challenge teach physics content? The David el Gnomo project met their original teamwork goal, but it hadn’t demonstrated how to teach content through an engineering design challenge, and the teachers were concerned. Why would they do this project if it didn’t teach their students any physics? From my perspective, they already did a project (their tower build) that didn’t teach any content, and they justified it because it taught teamwork and bonding. We discussed the merits of a relatively content-free engineering design challenge like David el Gnomo as being useful for teaching the engineering design process, a worthy goal unto itself because it emphasizes systematic data collection and improvement over the bane of science teachers: guess and check.

The teachers identified some new understandings after completing the activity: They liked how engineering design focused on divergent thinking followed by convergent thinking. Katniss said that just knowing convergent was coming boosted her confidence in even trying a widely divergent activity. Anna mentioned that she liked “how it gets at all the aspects though of science, and that it’s iterative, and it’s very creative.” Katniss suggested that the team could “do parts of this leading up to it, to make it more familiar” to the students, implying that she was already thinking about how she’d do a very natural and teacherly scaffolding of this process before going diving into the whole process at once.

I learned a lot about my assumptions during this October PD session, too. First, I felt some elements went really well. The teachers seemed to see opportunity in the engineering design process for changing their own instruction. Second, they were incredibly engaged in the activity and I saw that their engagement wasn't just because of some personal attachment that they had to David el Gnomo, it was also just simply engaging to set up and solve a problem. I was glad I'd planned for the teachers to actually engage in problem definition, prototyping and testing, instead of just reading about an engineering design challenge as an example, or about the engineering design process in the abstract.

But some things didn't go so well. I regretted giving the teachers a task that would have taken a full two hours to complete on top of wanting them to "zoom in and out," reflecting as teachers and students throughout. It was just too much time and their teacher time is precious. Based on their exit survey responses, I realized that my agenda of pre-planned PD session ideas was probably not going to be as helpful as I had hoped—they wanted to see physics content embedded in challenges so I would need to refocus on that and teach them to do the content-embedded planning by modeling it and having them practice it together, not by telling them about other ETF artifacts like rubrics or decision matrices. Lastly, I regretted telling them about engineering design as if I was an expert and they were catching up. The truth was that I wasn't an expert and they didn't have to try to achieve some benchmark that I possessed. This came back to haunt me in later months as Leslie and Anna tried the Pumpkin Chunkin' Challenge in their classes.

Leslie Plans the Pumpkin Chunkin' Challenge

Leslie planned a projectile motion challenge for right before Thanksgiving break. (Please see much more on this challenge in Chapter Five.) Leslie set a catapult challenge within the context of the annual Pumpkin Chunkin' Contest (a real-life pumpkin shooting contest held annually in Delaware). Leslie and I planned this project without her peers over two days and then shared the idea with Anna and Katniss.

Leslie delivered the challenge to all of her classes in four days spanning Thanksgiving break. Anna delivered it to two of her three classes. Both Anna and Leslie initially felt awkward instructing the challenge. They both worried about getting it right. Anna asked me during class if she was doing it right, and Leslie lamented at lunch after fifth that she was worried about having an expert observe her. After discussion and reflection, the two had different reactions: Leslie came to feel it went well, was really fun and had been a pivotal point in her understanding of engineering design. (Please see Chapter Five where I explore Leslie's pivotal points, including her concerns with this challenge and how she got past them.) Anna decided that even after she watched me teach it too, she just wasn't comfortable with the challenge and did not complete it with her last class.

Tensions Between Physics Teaching and Engineering Design

At the first planning meeting, Anna mentioned that she thought that the coffee filter lab they already did would be a good opportunity to try engineering design, and after her progress during the catapult, Leslie was motivated to get the whole team on board. This led to the parachute project—the first project the teachers planned all together.

Chapter 4 of this dissertation focuses on the tensions that these teachers encountered in their instruction of the Parachute Challenge: how they planned and taught with various emphases on engineering design and physics content, tensions around collecting enough data to make authentic engineering design decisions, and tensions around letting go the control of student success so students could explore divergent ideas and learn about productive failure.

iPhone Drop Challenge and Musical Instruments Project

After the parachute project, the group's engineering design planning took off. Katniss planned an engineering challenge for IB physics in January, and in February all three teachers came together to plan an "engineerized" iPhone Drop Challenge based on their previous year's extension project. This challenge offered arguably the most authentic engineering design experience with two rounds of design improvement and three rounds of testing, but still maintained an inquiry instruction stance in which students developed sense-making from investigative activities. Leslie later recognized that it was in the iPhone project that engineering design had felt the most comfortable, and it seemed like all cylinders were firing for the teachers even though the new engineering terrain was less comfortable than simply doing the packet they had done the year before with one culminating iPhone drop.

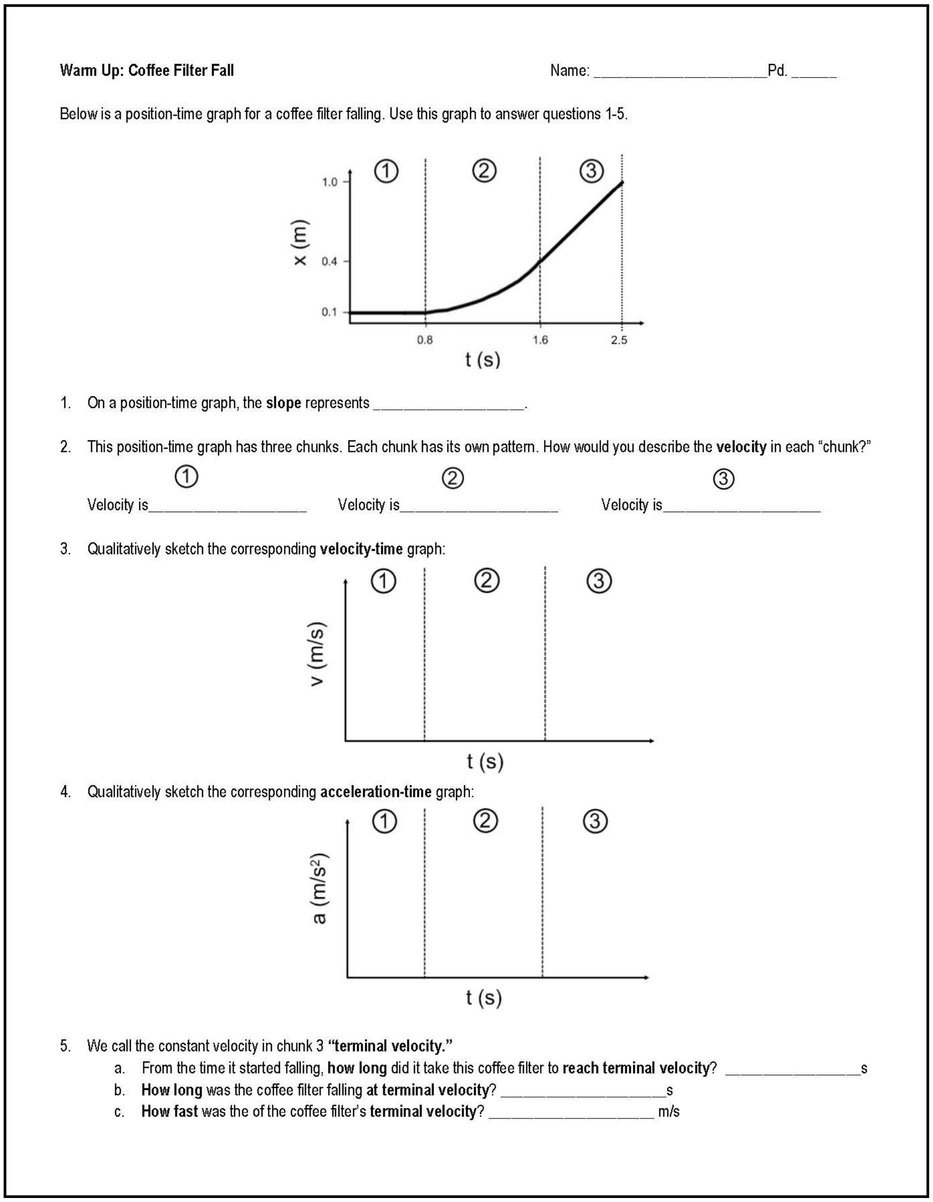
When the teachers moved from the iPhone Drop Challenge to the roller coaster project they all expressed relief to be back on familiar soil doing the roller coaster project exactly as they had in previous years—this was territory they knew well so they could anticipate sticking points, provide specific organizational structures (from team folder organization to, materials distribution and tracking). But as the roller coaster progressed and students seemed to be slapping coasters together without careful testing Leslie said that she really missed the affordances that iteration offered in the iPhone Challenge because in the roller coaster they only built one coaster, and after testing had limited opportunities to revise much less rebuild.

In their third interviews I asked Katniss and Anna what they thought about Leslie's sentiment. Anna said she wished the teachers had done more engineering design from the start of the school year so that the students would more naturally say, "think about some of our different ideas and sketch things out" before jumping into projects like the roller coaster. Katniss said she wished the students "had been more thoughtful" in the roller coaster.

During the last project of the year, the musical instruments challenge, the teachers tried scaffolding design exploration a little differently and had students gather information on three potential design ideas on the internet, drawing a "blueprint" and making materials lists for each before picking one to pursue and justifying that decision. The teachers liked this more than their usual, what instrument will you make? Because the students thought through several designs explicitly and reasoned why they would try a particular one. But the instrument building process involved relatively little systematic data collection, which frustrated several teachers. In the end, it was instructive of what engineering design is and is not, and created fodder for many discussions.

Even if it wasn't authentic engineering design there was still lots of opportunity for divergent student thinking. The teachers all recognized something else interesting; Anna's classes produced the widest variety and most ambitious projects by a long shot. In her classes were a full-size upright string bass, two working trombones, a bag pipes, hanging water-filled chimes, and electric and acoustic guitars. The other teachers also had water, length, woodwind, and percussion instruments, but many were exactly or closely similar to example projects the teachers showed: a metal tube xylophone, water-filled glasses, bottles or jars, rubber bands around boxes, and pan pipes. When we all recognized how far Anna's students had taken the project we speculated that the wide range of divergent thinking might have been allowed by the safety that Anna sets up in class. This is in direct contrast to the tension in her first Parachute Challenge, where by protecting students from failure she limited student divergent thinking and risk. By the end of the year Anna's students were widely diverging within the safe spaces she'd created.

Appendix 4.1: Parachute Design Challenge Warm-Up: Student Handout



Warm Up: Coffee Filter Fall Name: ______________________Pd. ______

Below is a position-time graph for a coffee filter falling. Use this graph to answer questions 1-5.

1. On a position-time graph, the **slope** represents ___________________.
2. This position-time graph has three chunks. Each chunk has its own pattern. How would you describe the **velocity** in each "chunk?"

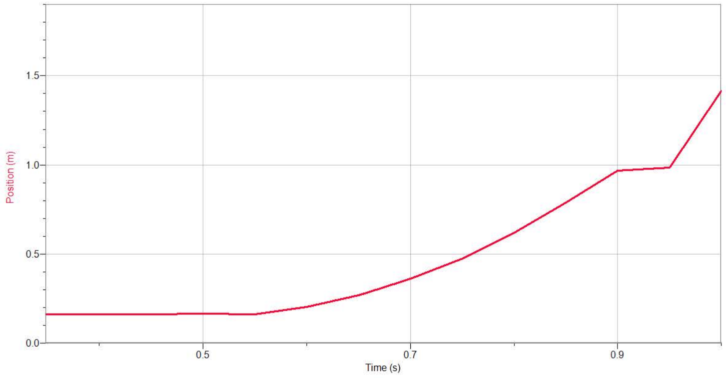
① Velocity is____________________
② Velocity is____________________
③ Velocity is____________________

3. Qualitatively sketch the corresponding **velocity-time** graph:

4. Qualitatively sketch the corresponding **acceleration-time** graph:

5. We call the constant velocity in chunk 3 **"terminal velocity."**
   a. From the time it started falling, **how long** did it take this coffee filter to **reach terminal velocity**? _________________s
   b. **How long** was the coffee filter falling **at terminal velocity**? _____________________s
   c. **How fast** was the of the coffee filter's **terminal velocity**? _____________________ m/s

Below is an actual position-time graph, recorded using a motion detector, for a coffee filter falling.



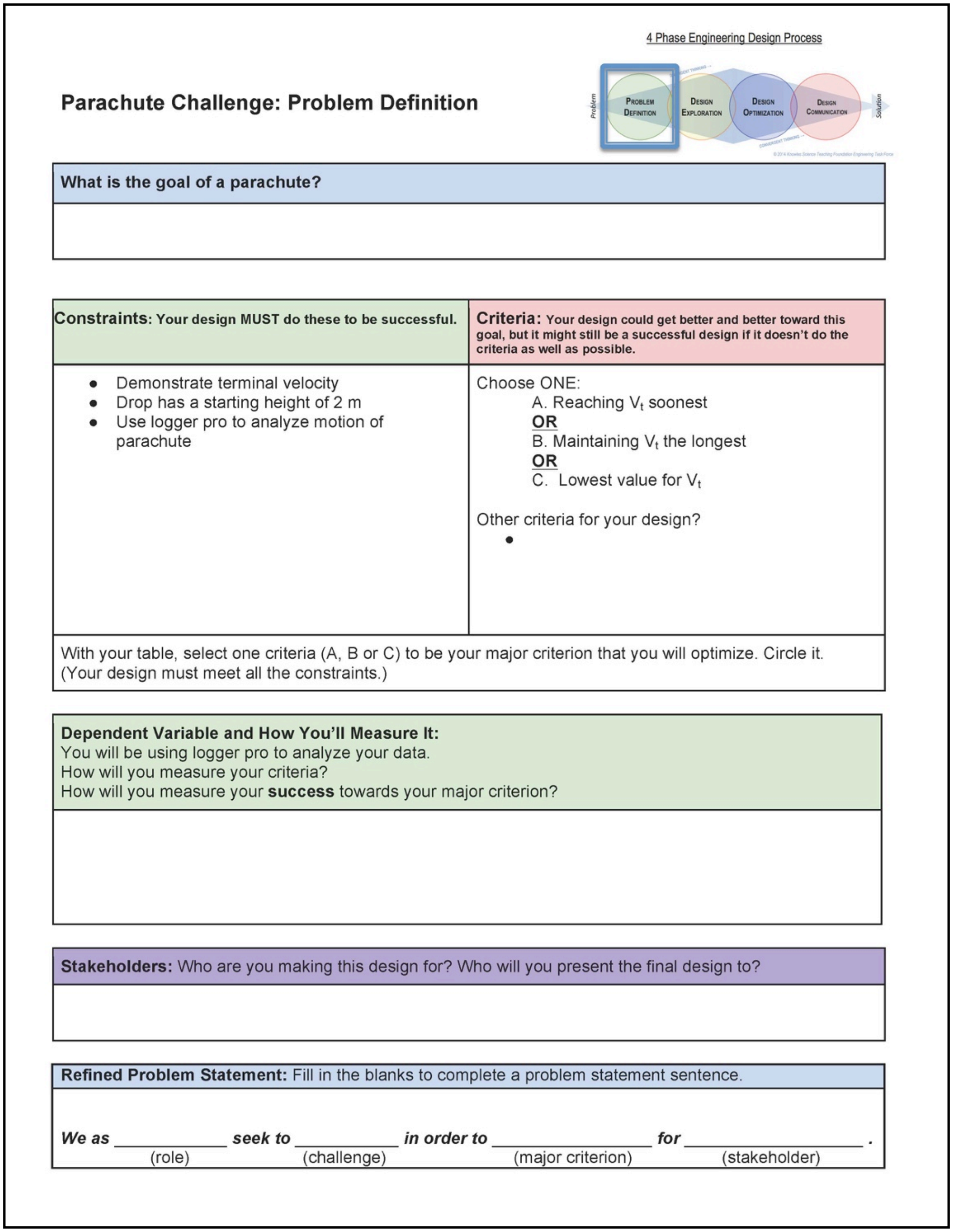
6. Draw dotted lines on the graph to divide it into three "chunks," one for each pattern.

7. a. From the time it started falling, **how long** did it take this coffee filter to **reach terminal velocity**? __________________s

   b. **How long** was the coffee filter falling **at terminal velocity**? ______________________s

   c. **How fast** was the of the coffee filter's **terminal velocity**? ______________________ m/s

Appendix 4.2: The Parachute Challenge Handout



4 Phase Engineering Design Process

Parachute Challenge: Problem Definition

What is the goal of a parachute?

Constraints: **Your design MUST do these to be successful.**	**Criteria:** **Your design could get better and better toward this goal, but it might still be a successful design if it doesn't do the criteria as well as possible.**
• Demonstrate terminal velocity • Drop has a starting height of 2 m • Use logger pro to analyze motion of parachute	Choose ONE: A. Reaching V_t soonest **OR** B. Maintaining V_t the longest **OR** C. Lowest value for V_t Other criteria for your design? •
With your table, select one criteria (A, B or C) to be your major criterion that you will optimize. Circle it. (Your design must meet all the constraints.)	

Dependent Variable and How You'll Measure It: You will be using logger pro to analyze your data. How will you measure your criteria? How will you measure your **success** towards your major criterion?

Stakeholders: Who are you making this design for? Who will you present the final design to?

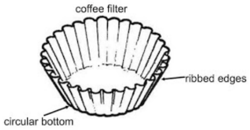
Refined Problem Statement: Fill in the blanks to complete a problem statement sentence.
We as ____________ ***seek to*** ___________ ***in order to*** ________________ ***for*** __________________ ***.*** (role) (challenge) (major criterion) (stakeholder)

Parachute Challenge: Design Optimization

4 Phase Engineering Design Process

Here is the most basic model of parachute:

Height of filter – .05 m
Mass of Filter - .001 kg



Variable selection for optimization.

Independent Variable:
Brainstorm some variables you could change that might impact your design's success.

•   •
•   •

Pick one of these variables to be your Independent Variable for testing. **Circle it.**

Your Dependent Variable is the data you said you could measure on the other side of this paper. **Write it.**

Data collection research question:

What is the effect of ______________________ **on** ______________________________**?**
(Independent Variable)   (Dependent Variable)

Check w/ Teacher

Collect data to drive your design decisions and improve your design

Make a data table and a graph to describe the experiment you did to help improve your design.

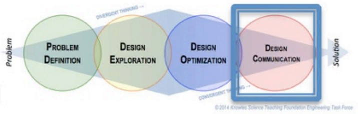
DATA TABLE:

IV: __________ ( )	**DV:** ________________________ ( )			
	TRIAL 1	**TRIAL 2**	**TRIAL 3**	**AVERAGE**

Graph Page

Select the Optimal Level of Your Independent Variable or Say Why There's No Optimal Level.

4 Phase Engineering Design Process



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Parachute Challenge: Design Communication

In the space below, write a letter to your stakeholder making a recommend parachute for your scenario. When sculpting this letter, think about:

- **claim** (statement of recommendation)
- **evidence** (data you collected)
- **reasoning** (interpreting data to support claim) when sculpting this letter!

(If you like writing on lines, you may attach your letter written on lined paper).

Next day WU: Last unit we assumed all things fell at -9.8 m/s^2 (acceleration due to gravity). But in this lab, we saw that eventually your object fell at terminal velocity (a=0).

Think about your optimized level of IV for your parachute. What is happening physically with your parachute, so that this optimal level makes sense? Feel free to use a diagram to help!

What common forces were acting on your model?

In what way were they pushing and pulling on your model to create terminal velocity? Draw them.

Appendix 4.3: Transcripts of Anna in Parachute Challenge

[00:58:50.20] [Anna is talking to the plant group]

Anna: So what does our data tell us? [She sounds tired and mad maybe?] How does mass affect terminal velocity?

St1: Uh, it's about that

Anna: Okay, so::oo if there's a, if it's a larger mass, it's reaching, it's going to be in terminal velocit::y… .

St2: ~Faster than?~

Anna: It's going to have, well actually, it's going to have a higher terminal velocity 'cause you guys used the slope right? So the lower the mass, the lower the terminal velocity. And you guys are looking for the, the lowest value [St1: yeah] for terminal velocity. So that would be your recommendation.

St1: So our lowest value would be this.

Anna: Yes. So it looks to me like with this graph, yeah, you're— the lower the mass, the lower the terminal velocity. So that would be your recommendation for… for your…Who are you guys doing this for again? You guys are consultants?

St1: Sky diving committee.

Anna: Ooh the sky diving committee. Yeah. So you're going to you know, recommend that they're going to use the lightest equipment right that's safe possibly.

——

01:07:04.07 Okay so maybe number of holes doesn't have an effect on downward— on speed? You could recommend not spending wasting money on putting perforations in your skydiving or having more space in between skydiving team. So as long as you can back up your statement give some evidence based on your graph you're fine. Ok?

[01:08:05.20] Anna: how do you think, how does mass affect the—

St14: Terminal velocity

Anna: Okay so start to think about your recommendations for the for the you guys, so you're going to want to make sure that they're using you know the lightest weight materials in order to fall…when they go to sky dive.

——

[1:17:02.01]

Anna: You're going to recommend to your stakeholders that you recommend the lightest the least massive equipment maybe that you want to…put on a diet…or you want to have—you found they'll stay—they'll have the lowest terminal velocity.

Appendix 5.1: Tagged Codes from MaxQDA

(This is not every tagged entity in the data set)

1st Level	Sub Level a	Sub level b	Sub level c
Title quotes			
Projects			
	musical instruments project		
	Roller coaster		
	Pumpkin		
	iPhone		
	parachute		
Productive Resources			
	Engineering and STEM are buzzy		
	ready for change		
	teacher moves		
		how to handle sticking points/nerves	
	process emphasized		
	gives agency to students		knowledge is constructed by students
	Less T voice		knowledge is constructed by students
	Active engagement		knowledge is constructed by students
	"Bigger Pictures"		*Learning is enriched by novel applications and demonstrated by transfer to new contexts*
		Context	*Learning is enriched by novel applications and demonstrated by transfer to new contexts.*
Conceptual Framework			
Foundations			

of science			
	NOS		
	patterns		
Growth mindset			
	preconceptions		
	Thinking		productive struggle is learning
creativity			*Learning is enriched by novel applications and demonstrated by transfer to new contexts.*
Physics			
	physics content in engineering		*Learning is enriched by novel applications and demonstrated by transfer to new contexts.*
	Physics course availability		
Reform			
Standards			
	NGSS		
Teachers			
	holding some back from the students to increase S engagement		
	Changing curriculum year over year		
	Collaboration		
	Social constructivism conceptual change teacher moves		
	Teacher epistemology		
		engineering in ed is concrete	
		epistemology	
	teachers decide		
	(Not) how I learned it		
	more STEM teachers		

		better STEM teacher training	
	Teacher support		
Assessment			
Engineering			
	student gains from engineering		
		productive failure	
		Active environment	
	engineering benefits		
		teaches new content	
		practices content	
		teach the problem-solving design process	
		21st cent skills	
	engineering in US pre NGSS		
	eng courses offered		
		Felicia	
	Engineering Design		
		divergent thinking	
			Risk Taking
		Stakeholder	
		design communication	
		design optimization	
		design exploration	
		problem definition	
Teacher prep			
	teacher engineering continuum		
		Teacher stress!	
		more advanced teacher engineering	

			“Spread”
		teacher novice engineering concepts	
Student gaps			
	underrepresentation		
	racial/ethnic gaps		
PD			
	stress due to being observed		
	Best practices		

Appendix 5.2: "Domains and Themes I've Noticed" Document

- From 10.15.14 field notes—there was a difference in how the teachers (LN and K) ran the beetle activity. Katniss ran the animation straight through several times –the challenge was engaging. Also talked to her about the kid who was obviously variously engaged that day on 10.21.15
- "IB brain" versus physics instruction
  - "IB Brain" is how Leslie describes Katniss's tendency to let IB practices and norms (even curriculum) slip into regular planning and teaching.
- Anna: relationships paramount
- Anna: apologetic and giving authority to students (11/18/15)
- Katniss: maybe lower expectations between regular vs. IB physics?
- Context is engaging!

  -Teachers engaged in David el Gnomo

  -Students engaged in the beetle

  NOT: Students not engaged in Katniss lecture on day of beetle in 4th period on 10.15.15

    - Engagement heals behavioral problems!
- I'm already seeing some limits—time (I needed more of it for my PD) so is that a conclusion?

- Distinction between divergent and convergent phases/thinking helps teachers feel comfort with engineering design and can serve as an instructional tool. (Restated at proposal defense)
- Leslie Nope: novice/expert interaction with engineering design, ownership and mastery of engineering design is differential in front of students versus with me.
- Katniss: Risk-taking and expectations differential between IB Physics and Regular Physics regarding engineering possibilities. Leslie Nope points out that Katniss's "IB Brain" influences what Katniss teaches in physics
- Anna: relationships paramount, apologetic to students, colleagues
- Engineering design must involve science content learning—changing opinions over time

12.16.15

- Anna uncomfortable with engineering design project implementation because she a) lacks a solid physics background and/or b) lacks a background in teaching by inquiry.
    - § A) if her way of being comfortable is to have one set of correct solutions in her hand that she then writes on the board and the kids write down (and I've seen it a bunch) then having choice feels too uncomfortable, even if the choices are vetted by her planning team.

    - § B) open-ended inquiry is a big leap for lots of teachers, and the IB teachers *had* to do it, even though it was strange. They both came to enjoy it. Open-endedness in engineering design projects is like open-endedness in inquiry, so lacking that training is a step into the unfamiliar without a pattern to follow, without experience to back up the claim that this crazy thing can work.
  - CHECK: are IB teachers in general better with this kind of choose-your own adventure engineering design challenge?
- Anna: Less things to worry about =better. Less DV choices for students is less to worry about.
- Anna: content issues. 1/7/16 Force pairs versus 3rd law versus force diagram.—no it's okay, she just didn't explain her issue to me very well. In instruction, the steps she went through were right, she reasoned it correctly, and did it correctly on the board.

3/1/16

- Practice to Parrott. The teachers seem to develop a dialog in practice, or planning that later they repeat. I think they repeat it more over time, so it is engrained, which makes me think either it increases confidence or it happens more with confidence. Examples: the swimmer's case. Repetition in Katniss's second interview.
- Budget might be a concern, but **Privilege might also be a "real world" concern.** Would some teachers not be able to do this? Sure. But would some

teacher hesitate to do a project because “it would offend” their colleagues or previous colleagues? Is the idea of elite schools “offensive?”
  - Is it money or is it the activity itself?
- The real world gets in the way. Travel schedules, sickness, family
  - Alaska
  - Flu/losing voice
  - Anna’s dad
    - All led to Anna and Katniss not thinking the iPhone Drop Challenge was awesome, but Leslie telling Katniss, if she’d been in class the whole time she would have seen it’s good.
- Tension between making a “good” or “real” product, and not costing too much/not taking too much time.
- Evan really wanted to be mindful of having students have the opportunity to make a good product, not just an amateur job with string and tape. And he stressed that again with making the videos, he didn’t want them to be too amateur, he wanted them to be really good products so giving them adequate time and support was important to him
- All the Merlin teachers wanted them to make a real functioning case, and there was some conversation in planning that the cases were too big to actually use, but then again, they wanted to also ensure that it didn’t cost anything to make them.

  - If they'd gotten sponsored to design 3-D printed cases, and lots of old phones to test before, say, battery recycling, would that have mattered to them? Would Katniss have felt better about the offensiveness?

- School deficit:

· Katniss in third interview (second try interview):

  - "Interdisciplinary collaboration, I guess, which I don't really see at [Merlin] as much."
  - There are some schools where like…

Teacher downplays worth

Katniss (Interview three, second try)

  - Willing to work for free "So if there's a role, like it doesn't, I'm fine with unpaid stuff, like, that's the story of my life [laughs]"
  - Explaining vectors to Felicia, she said, explaining stuff to her, because I had just taught them

Iteration reflects a growth mindset.

LK on 11.23.15

6:00	"You guys don't have any other hopes and dreams for your catapult?"	ideas about criteria and constraints

	“but that’s okay, you haven’t necessarily failed if you’ve…”	

Appendix 5.3: Transcript of Audio Memo on December 15, 2015

Typed memoing on the transcript in brackets is from April 27, 2016, prepared in Inqscribe from .mp3.

[00:00:01.14] Katey: Man, I just realized, I was just thinking about class tonight and teaching like students about inquiry, and how I want to do this level four, not even giving them the question kind of inquiry tonight, and I just realized that one of the things about Anna and eliminating the DVs

[QUESTION FOR Anna: why didn't she just change the lab?]

[00:00:20.04] Katey: is that essentially it takes it from giving them a level four, where you haven't even asked the question but you sort of scaffolded a question, to uh maybe, I don't know, like a level 3? where you say what is the effect _on_ [emphasis] the velocity, the terminal velocity, the slope? It's like you, you haven't given them the procedures, maybe, but you have given them the question, and in some ways you're scaffolding the procedures quite a lot too but, so it just reduces that inquiry level.

[A-ha! so this is an argument why IB science teachers, or teachers whom have taught

IB when the IA was still open-ended might have an easier time trying this kind of choose-your own DV engineering design project. (Just physics or all did this open IA thing?) Remember, this is but one kind of engineering design challenge. in some hierarchy or list of types of engineering design problems, which I should probably make]

[00:00:54.27] Katey: And I wonder if Katniss and Leslie would talk about that inquiry—well, Leslie did talk about it right? she talked about doing that in terms of the IA, and how she's done it over and over with the IA

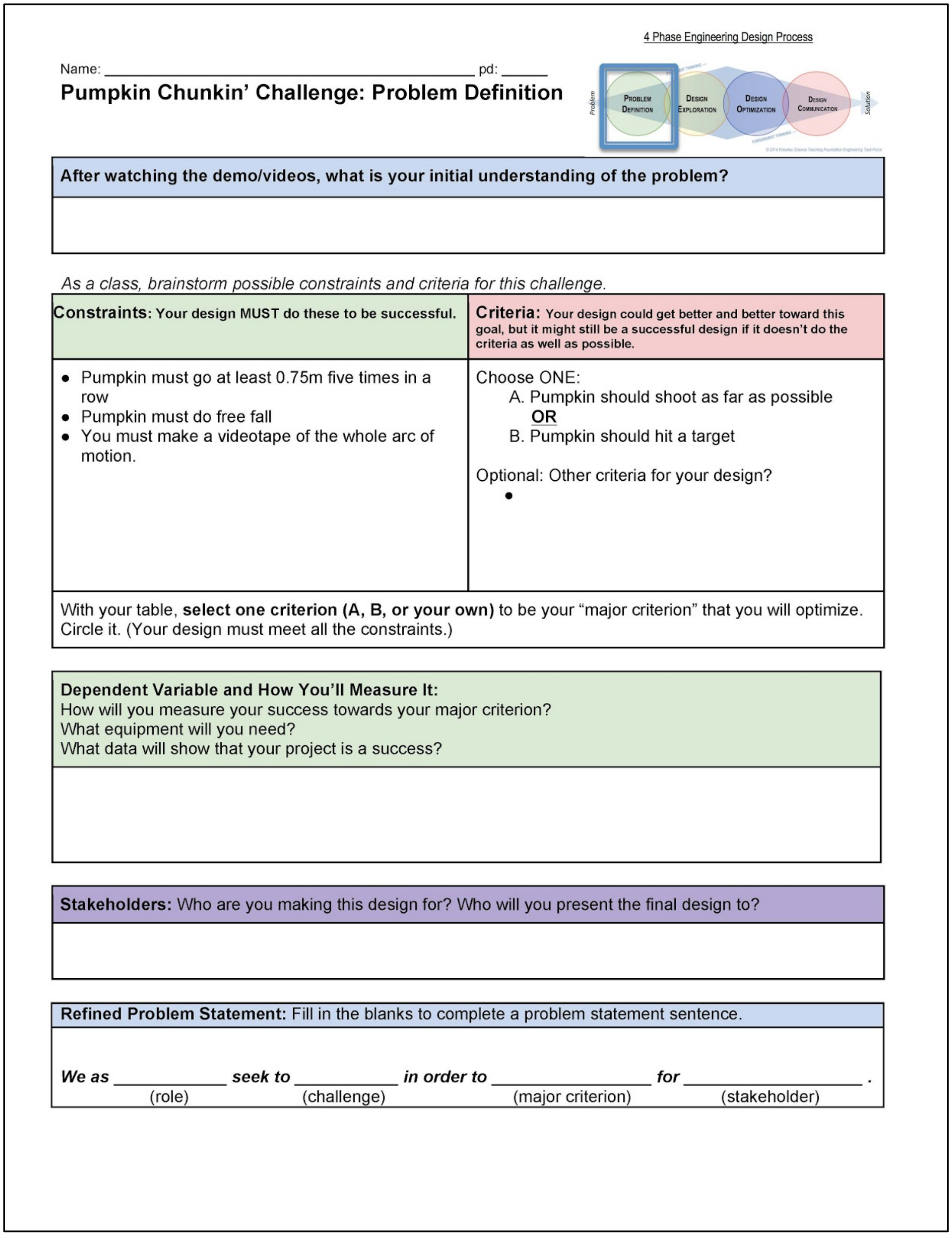
[and I'll note in the IA lab groups weren't allowed, so kids had to do it alone, so you'd also have 25 different open-ended inquiry projects going on at once.]

[00:01:08.03] and how it was like, she said, 'oh so here you're burning spaghetti, like what are you doing?'

[here LK was referring to a conversation we had where she was saying she missed the spaghetti lab, and they hadn't restocked spaghetti since the IA, because they used to just say, investigate the spaghetti, and students did all kinds of things, bridges, sure, but burning, and calorimetry, and conductivity, etc.]

[00:01:14.01] You know, like kids were just allowed to do things and try to figure out sense and meaning from them, so maybe that's a big deal, that um, that to do this sort of open-ended thing it is helpful, maybe not required, but it might be helpful if you are comfortable with level four open-ended inquiry.

Appendix 5.4: Pumpkin Chunkin' Tool 2015 v6 [KNOPE]



4 Phase Engineering Design Process

Name: ____ pd: _____

Pumpkin Chunkin' Challenge: Problem Definition

After watching the demo/videos, what is your initial understanding of the problem?

As a class, brainstorm possible constraints and criteria for this challenge.

Constraints: Your design MUST do these to be successful.	**Criteria: Your design could get better and better toward this goal, but it might still be a successful design if it doesn't do the criteria as well as possible.**
• Pumpkin must go at least 0.75m five times in a row • Pumpkin must do free fall • You must make a videotape of the whole arc of motion.	Choose ONE: A. Pumpkin should shoot as far as possible **OR** B. Pumpkin should hit a target Optional: Other criteria for your design? •

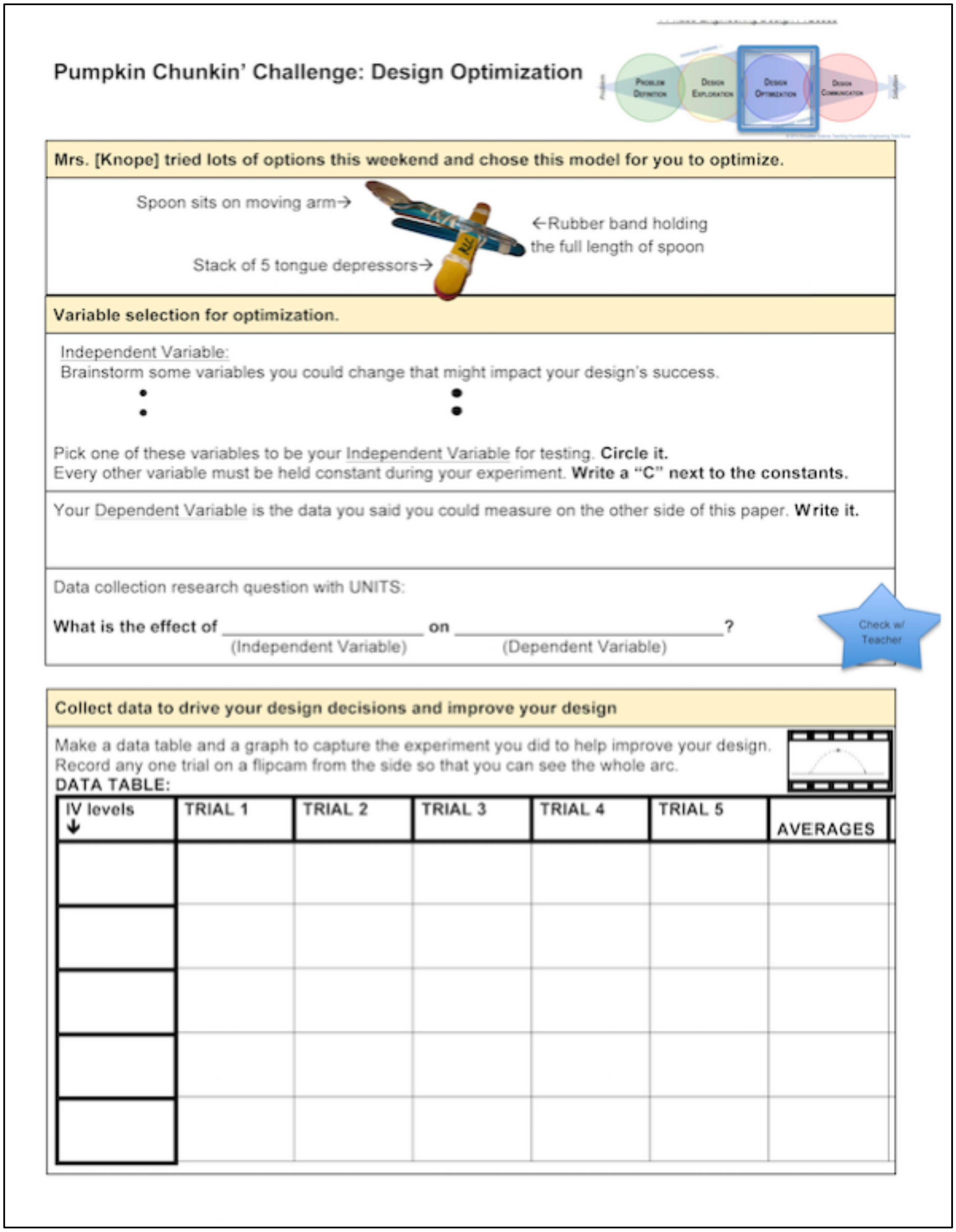
With your table, **select one criterion (A, B, or your own)** to be your "major criterion" that you will optimize. Circle it. (Your design must meet all the constraints.)

Dependent Variable and How You'll Measure It:
How will you measure your success towards your major criterion?
What equipment will you need?
What data will show that your project is a success?

Stakeholders: Who are you making this design for? Who will you present the final design to?

Refined Problem Statement: Fill in the blanks to complete a problem statement sentence.

We as ___________ (role) ***seek to*** __________ (challenge) ***in order to*** _______________ (major criterion) ***for*** __________________ (stakeholder) **.**



Pumpkin Chunkin' Challenge: Design Optimization

Mrs. [Knope] tried lots of options this weekend and chose this model for you to optimize.

Spoon sits on moving arm→

←Rubber band holding the full length of spoon

Stack of 5 tongue depressors→

Variable selection for optimization.

Independent Variable:
Brainstorm some variables you could change that might impact your design's success.

-
-
-
-

Pick one of these variables to be your Independent Variable for testing. **Circle it.**
Every other variable must be held constant during your experiment. **Write a "C" next to the constants.**

Your Dependent Variable is the data you said you could measure on the other side of this paper. **Write it.**

Data collection research question with UNITS:

What is the effect of ______________________ **on** ______________________?
(Independent Variable) (Dependent Variable)

Check w/ Teacher

Collect data to drive your design decisions and improve your design

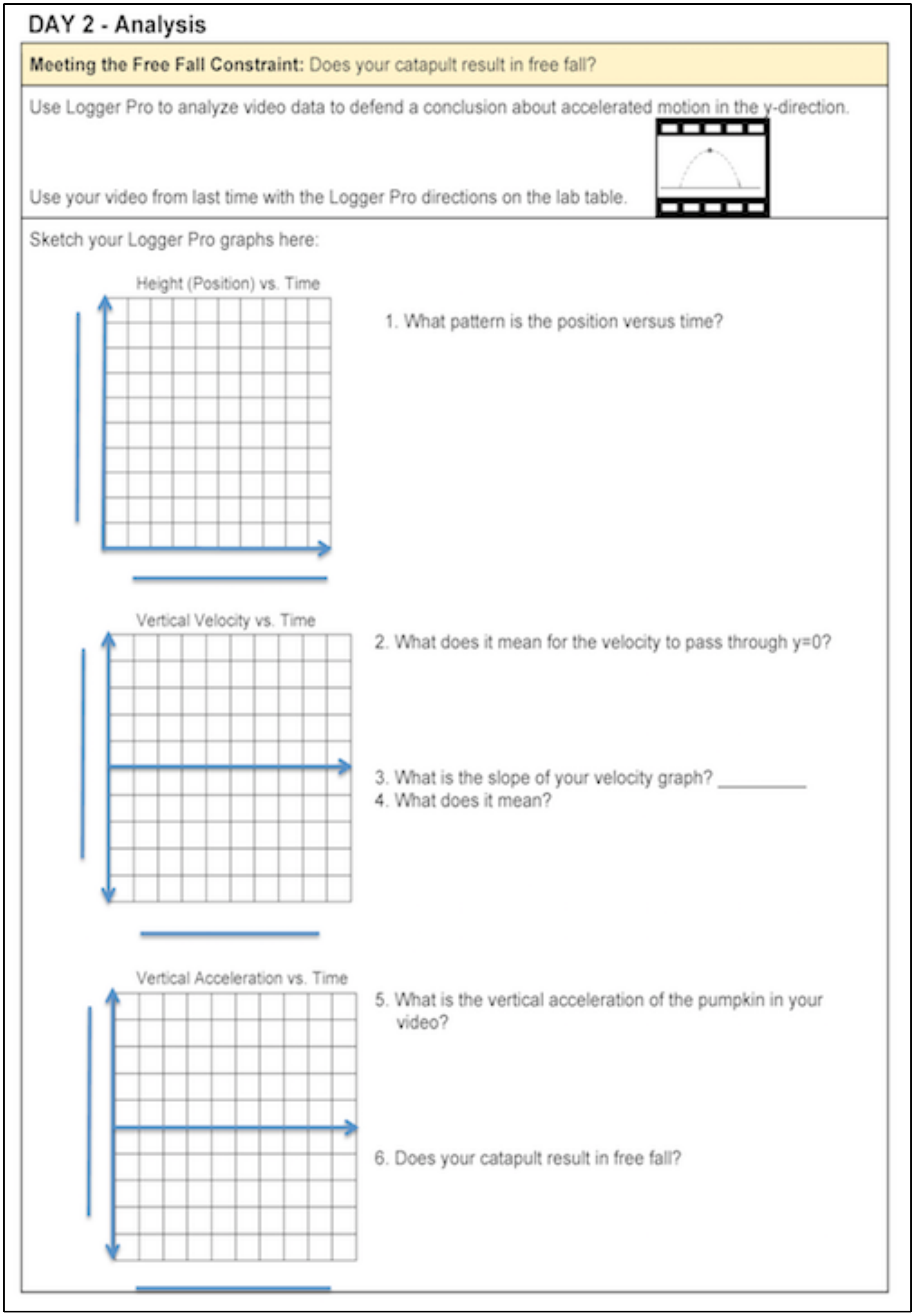
Make a data table and a graph to capture the experiment you did to help improve your design.
Record any one trial on a flipcam from the side so that you can see the whole arc.

DATA TABLE:

IV levels ↓	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 5	AVERAGES

Graph Page

From your graph, select the optimal level of your independent variable or say why there's no optimal level.



DAY 2 - Analysis

Meeting the Free Fall Constraint: Does your catapult result in free fall?

Use Logger Pro to analyze video data to defend a conclusion about accelerated motion in the y-direction.

Use your video from last time with the Logger Pro directions on the lab table.

Sketch your Logger Pro graphs here:

Height (Position) vs. Time

1. What pattern is the position versus time?

Vertical Velocity vs. Time

2. What does it mean for the velocity to pass through y=0?

3. What is the slope of your velocity graph? __________
4. What does it mean?

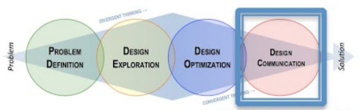
Vertical Acceleration vs. Time

5. What is the vertical acceleration of the pumpkin in your video?

6. Does your catapult result in free fall?

Pumpkin Chunkin' Challenge: Design Communication

4 Phase Engineering Design Process



Defend your design choices: Present your final design choices to your stakeholders and justify the decisions you made with data.
Did you make a successful design? *Did you meet the constraints?* *How well did you achieve the criteria?* *What data supports your design decisions?*

Public Prototype Test: You will have the opportunity to publically prove your prototype to your client (stakeholder).
Yes!

Appendix 5.5: More From Leslie's Fourth Interview

Leslie: Oh, and, personally…yeah, I'm teaching the same subjects again for the second year in a row, and I just really like new challenges when it comes to curriculum and how to teach kids, and I just feel like I already knew what they were going to say to me, all their misconceptions and etc. This was an exciting, new challenge. When you first presented your project to us I think the unfortunate part of the first presentation was that you were showing us the engineering design process…You were saying this is something that you already do, but the problem was that our goal in that tower thing has nothing to do with curriculum, it has nothing to do with teaching them engineering. Like our goal that day is just teaching them how to collaborate with people.

Katey: You mean the way that you already do it?

Leslie: Correct. Correct. When you were like here's how you could do engineering design process in this tower thing that you've already done in that school year, right? [inaudible 00:34:45] is like ugh, but, but I don't want to change that because it's already meeting the goal that we have, right? I had to stop myself and say, "Okay, but open your mind to what else this could be." necessarily, because you were just using it as an example.

I think, also, [Katniss's] situation was, oh, gosh, well, how do we actually put content into this because we don't use this for content at all, right? The time came…where I had those two extra days before Thanksgiving and I was really excited to just go for it, and just say, all right, we could do something incredible with this catapult, whatever. Katey, how the heck do we make this happen?

You and I sat down and tried to figure it out, and that first day that I presented it, it was first period, and it was terrifying because I didn't. One, because I was nervous that there was a way I had to do it. That you were like, "Well, she's not doing that the right way." You know? Two, I just didn't really understand what the end goal was. Like you had definitely told us that it's just about getting them exploring in this realm, but I still was feeling like they have to get to this final equation, and they have to get to this final understanding, and they have to get to this final whatever, whereas, honestly, with that project we were using some physics, right? We were using some data analysis skills and we were mapping it out, and everything, but, honestly, the actual goal of that project was to introduce them to what the engineering design process was…but I wasn't mentally ready for that I don't think, and, so, I was really wigged out by what was happening. It was total chaos. Which was…I came to be okay with, but…Just hard to do something again for the first time, with your student for the first time…Like first year teacher status is kind of what it was bringing me back into because it was completely new.

The next day though…I think maybe even seventh period. After we talked it out during lunch, I felt a lot better. Then, sixth period the next day when I taught it again was way better. Just way better, I think. That turned out to be a really fun, crazy, but fun project that, again, I got to start seeing different kids take leadership on. They were really coming to understand what it meant to measure things, and the skill, the value…of just skill set was starting to come up. They were using good words, good vocabulary, etc.

Appendix 5.6: Hypothetical Engineering-Design Instruction

In engineering-design instruction, one might expect to see a real-world problem posed by the teacher to the students. The teacher will likely have set up the entire challenge so that the students need to test their design in a way that identifies a physical relationship. This is a tricky effort—creating a contextual need for some new or revised product that could be made in a highly diverse bunch of permutations while expecting that every possible solution will have to demonstrate or indicate a need for some physics learning.

The teacher might first create space and time for students to explore the problem with a group and without teacher intervention. The students would document their assumptions, givens, questions, research, and articulate the problem in their own words with a comprehension for the constraints of the problem space (both hypothetical and real) and the criteria (one or more) they would like to try to optimize.

The teacher as "client" could remind students of knowns and as the "teacher" provide resources (material data sheets, measurement tools, laboratory materials), but ideally they would not participate as an "engineering team member" so that the students could define the problem themselves.

Once the problem is defined, and even as it's being defined, students might be thinking about what could work to solve the problem keeping track of ideas via sketches and writing. As certain ideas come together in the abstract, they may also be coming together in physical models with constant critique of ideas against the definition of the problem space. Students might be naturally trying ideas out with their hands, tinkering, playing with materials, or rapid prototyping.

The teacher might monitor students and intervene as a resource, not a teammate or a critic. The teacher should resist offering judgment and making contributions towards the design because the teacher's natural authority in the class might screw up the delicate role-play of authority that the students are in—they may be invested in the context of the problem, but they are still in school and the teacher is still an authority whose opinion could sway the creative design process away from student ideation.

But the teacher isn't impotent, he can still offer supports for prioritizing criteria (such as a pair-wise comparison charts), thinking about stakeholders (conferences or Skypes with a client), or planning future design actions (Knows, need-to-knows, next steps, design models, or brainstorming effective testing), etc. He could: ask students quasi-mechanistic prompts here to encourage students to make sense of the underlying mechanistic science within the design space; emphasize the benefits of generating many ideas instead of just demanding a minimum number; be resourceful with gathering and providing materials as much as is reasonable for a given school, context, or spread of day; press students to justify their decisions in light of the constraints and chosen criteria; remind students to track the development of their ideas and solutions over time; and push students to create tests for designs as they are being invented.

Eventually the students might come out with one best design idea, and need to test it, improve it, and generally optimize it. If an inquiry instruction-like approach is followed, then students as could design the testing experiments needed to inquire about the design's success. Knowing that there are many dimensions of testable variables for any given phenomenon and object, naming and negotiating the multi-variable problem could be challenging for students (and adults) (NAE and NRC, 2009). The teacher could remind students of the need for appropriate variable management and \ data collection, ideally already normalized in inquiry practices.

If the teacher has a physics agenda, the presence of various lab materials can be suggestive, as can technical documents for using lab materials, etc. just like it is in open inquiry instruction. But as given materials can be suggestive the teachers might try to remain clever in not telegraphing intentions too much.

All appropriate scientific inquiry conventions would still need to be followed and students would gather enough data to draw conclusions and defend against random error, testing extremes and limits to confirm their conclusions, and then use the data to identify areas of strength and weakness in their designs. The teacher throughout testing might be rather hands-off, but that assumes students already know how to scaffold an investigation into some element in their design. The teacher could act as a technical lab consultant or build in peer check-ins, group critiques, or preliminary result sharing sessions to give the students feedback without interrupting their group dynamic with teacher authority.

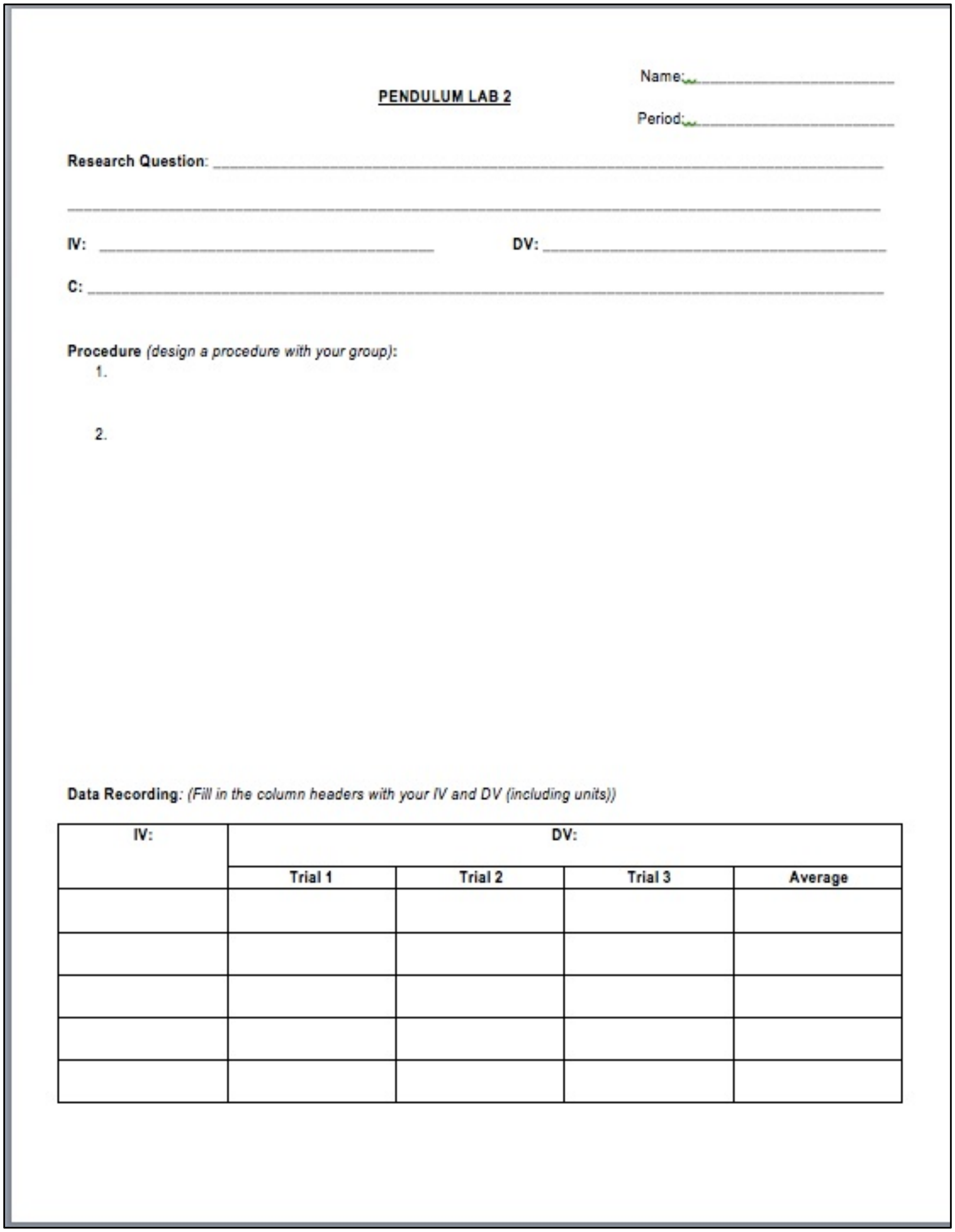
After testing the students should want to revise their product design, their expectations and criteria or even their constraints for what is possible and do more research, then they should be motivated to prove it’s better by testing it again. To really emulate authentic engineering design the students need the space and time to make adjustments, and test again before finalizing a design recommendation or product. But time to revise is in tension with the available time of the class (see Chapter 4, tension 2). Class time management is the teacher’s responsibility. Here the teacher could either provide adequate time to improve the designs, he could cut off the design cycle and say, ‘just give me what you’ve got,’ or he could ask for future steps, a ‘if you had more time’ approach. Whenever the teacher decides to end it, the expectation for completion should be made clear as an initial constraint.

Students have to show mastery in school, and this challenge should be no exception. Students should be asked to show mastery of their thinking and designing processes by presenting a representation of their final design (prototype, model, sketch, etc.) and justifying the design’s components (structure, function, materials) in light of the criteria or purpose desired and tradeoffs including cost, impact, waste, risks etc. A client and the teacher would likely want to see evidence of thinking about the thinking in the project. Likewise, students would have to show mastery of the physical relationships they “discovered” or saw via testing their object. They can draw patterns from the data and write those patterns as equations, they should utilize data interpretation skills such as making a best-fit line, examining error, linearizing non-linear functions to find accurate functions, studying dimensional analysis, testing limits to confirm the ranges of found functions, and conducting additional research to buttress or poke holes in their conclusions.

Over and over in this scenario, what the teacher does can impact the student's actions. I've attempted to point out places where the teacher's actions can scaffold student thinking and processing and where teachers should be wary of hindering student thinking and processing. If the teacher is providing enough space and instruction then the students have the opportunity to do the four-phase model, a version of authentic engineering design, even though it's hobbled a bit to fit into school structures (classroom, time and content). A key assumption is that if the teacher isn't doing it right then the kids can't do the full model.

But providing that instruction and space for students to do the full model is really hard. In my Merlin data, though, I have evidence of this happening in more and less directive ways (see chapter 4), and in Leslie's case I've gone deeper what resources might have contributed to the instruction that I saw.

Appendix 5.7: Leslie's Pendulum II Patterns Lab Pages



Name:________________________

PENDULUM LAB 2

Period:________________________

Research Question: ____

____

IV: ______________________________ **DV:** ______________________________

C: ____

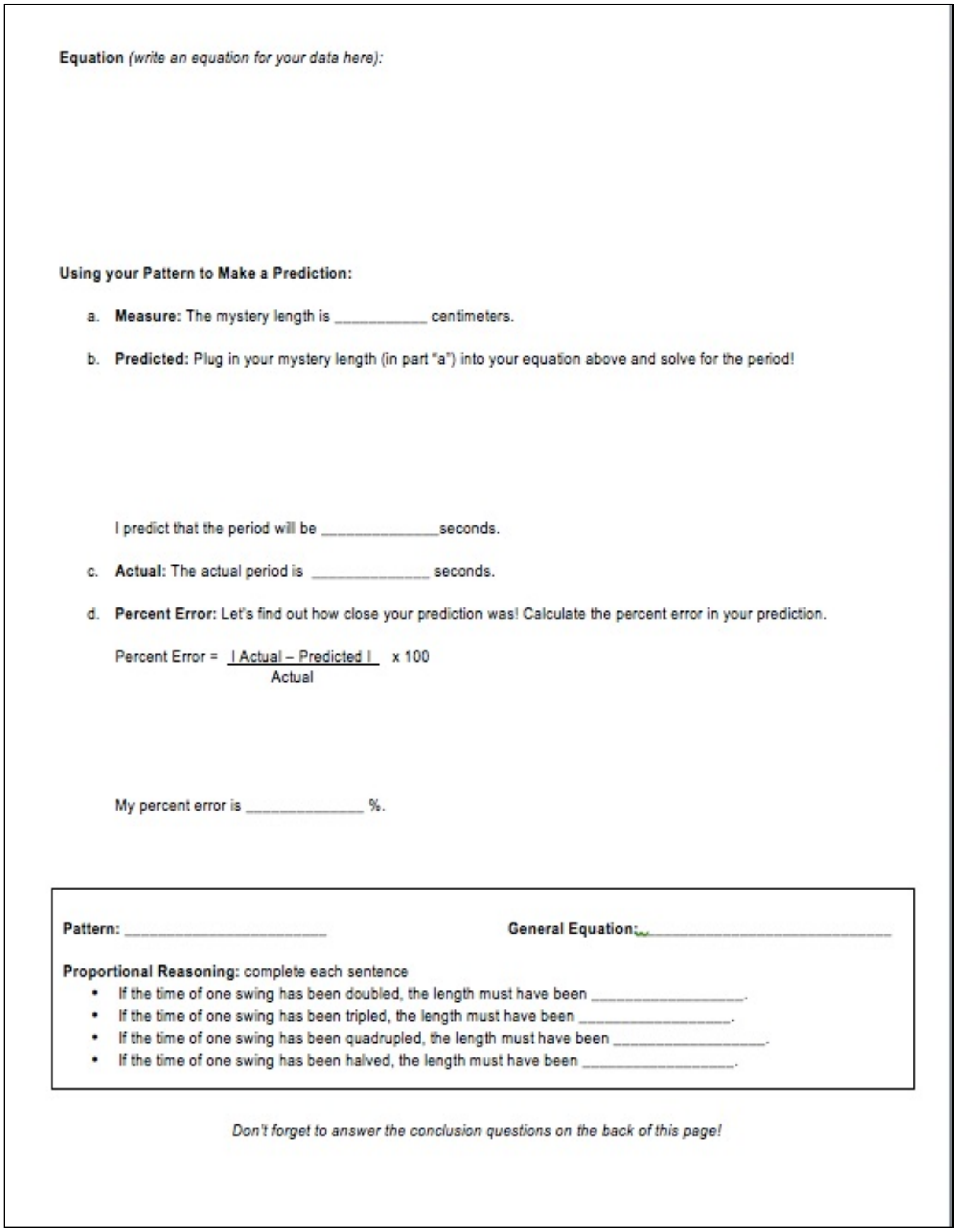
Procedure *(design a procedure with your group)*:

1.

2.

Data Recording: *(Fill in the column headers with your IV and DV (including units))*

IV:	**DV:**			
	Trial 1	**Trial 2**	**Trial 3**	**Average**



Equation *(write an equation for your data here):*

Using your Pattern to Make a Prediction:

a. **Measure:** The mystery length is ___________ centimeters.

b. **Predicted:** Plug in your mystery length (in part "a") into your equation above and solve for the period!

I predict that the period will be ______________seconds.

c. **Actual:** The actual period is ______________ seconds.

d. **Percent Error:** Let's find out how close your prediction was! Calculate the percent error in your prediction.

$$\text{Percent Error} = \frac{|\text{Actual} - \text{Predicted}|}{\text{Actual}} \times 100$$

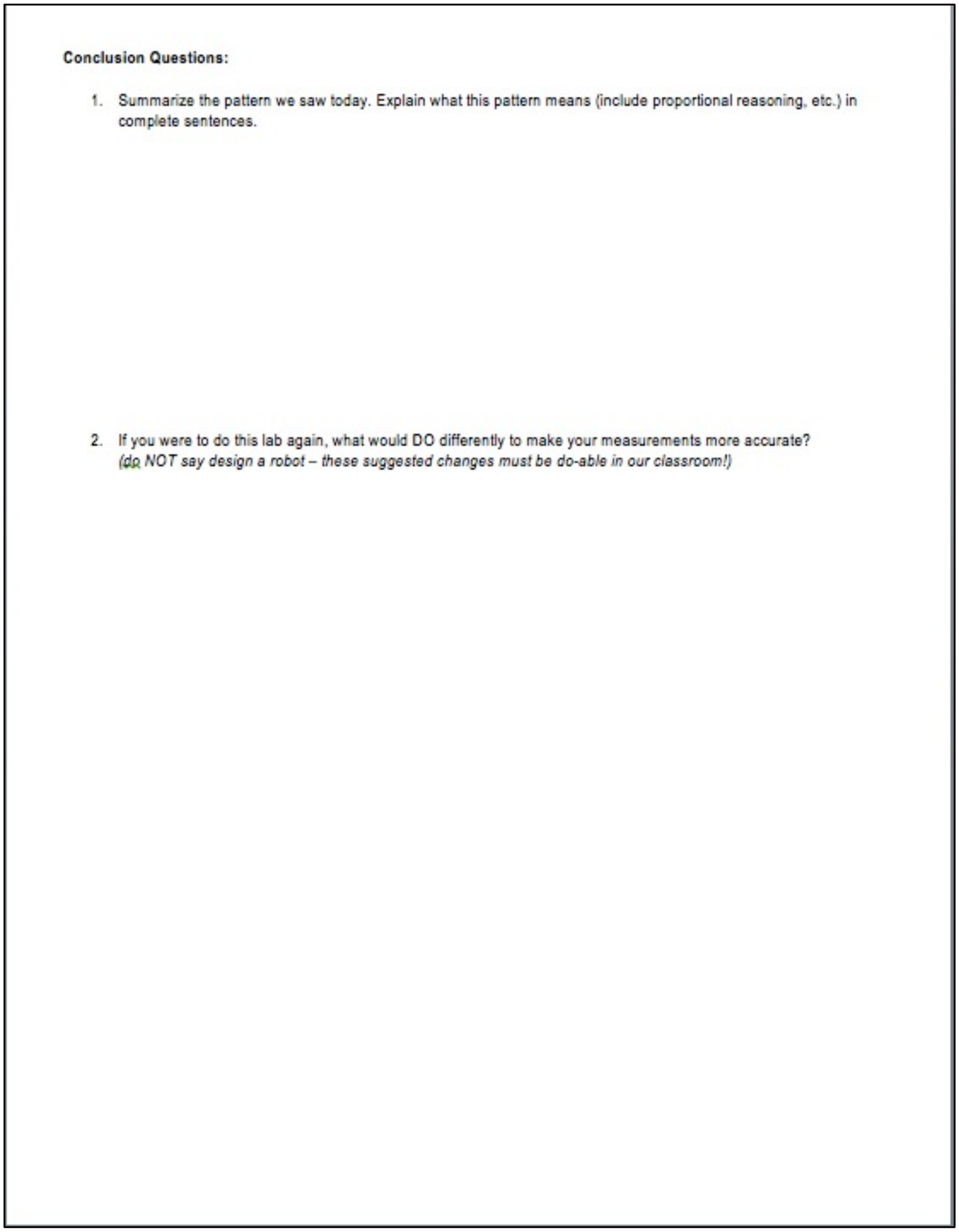
My percent error is ______________ %.

Pattern: ________________________ **General Equation:** ______________________________

Proportional Reasoning: complete each sentence

- If the time of one swing has been doubled, the length must have been __________________.
- If the time of one swing has been tripled, the length must have been __________________.
- If the time of one swing has been quadrupled, the length must have been __________________.
- If the time of one swing has been halved, the length must have been __________________.

Don't forget to answer the conclusion questions on the back of this page!



Conclusion Questions:

1. Summarize the pattern we saw today. Explain what this pattern means (include proportional reasoning, etc.) in complete sentences.
2. If you were to do this lab again, what would DO differently to make your measurements more accurate? *(do NOT say design a robot – these suggested changes must be do-able in our classroom!)*

Appendix 5.8: Another Look into Leslie's Back to School Night Day

The longest day of the school year is not the first day of school, or the last day, or even the day right before winter break, it is Back To School Night day. Leslie would be at school from 7:30 am to 9:30 pm. She had her other outfit for BTSN hanging on her cow-shaped hanger in the closet, and in-between classes she was working on her presentation for BTSN. This would be her eighth BTSN, but it wasn't less nerve-wracking. She needed to convey to adults that the inquiry-style instruction she was doing with her students was developmentally appropriate, safe but rigorous, and bottom-line, it was a great way to learn physics.

She could already anticipate the parent and guardians' hesitations: parents who themselves were taught in traditional physics classes—where a teacher lectured at students to teach content—might wonder why their child had no lecture notes to show at home. If a sibling had been in a different physics teacher's class in some prior year they might have expected that by the end of September their student would have mountains of physics homework, be drilling and memorizing kinematics equations, or be flabbergasted with frustration over how an object could be moving if no force was actively pushing it.

Leslie was not lecturing. She and her planning colleagues were facilitating an inquiry-focused graphical patterns discovery unit that would set their students up for successful data analysis skills the rest of the year. For Leslie, success meant they would learn how to capture an appropriate range of reliable data, to find patterns in data by graphing, fitting a curve, linearizing the curve to test a function's fit, and reasoning with evidence. She also hoped that they would be able to do this more or less on their own, to be spun up and sent off to discover, and that is why even from day the students had been puzzling, working in the lab, thinking and reasoning together with their groups, without much advice or intervention.

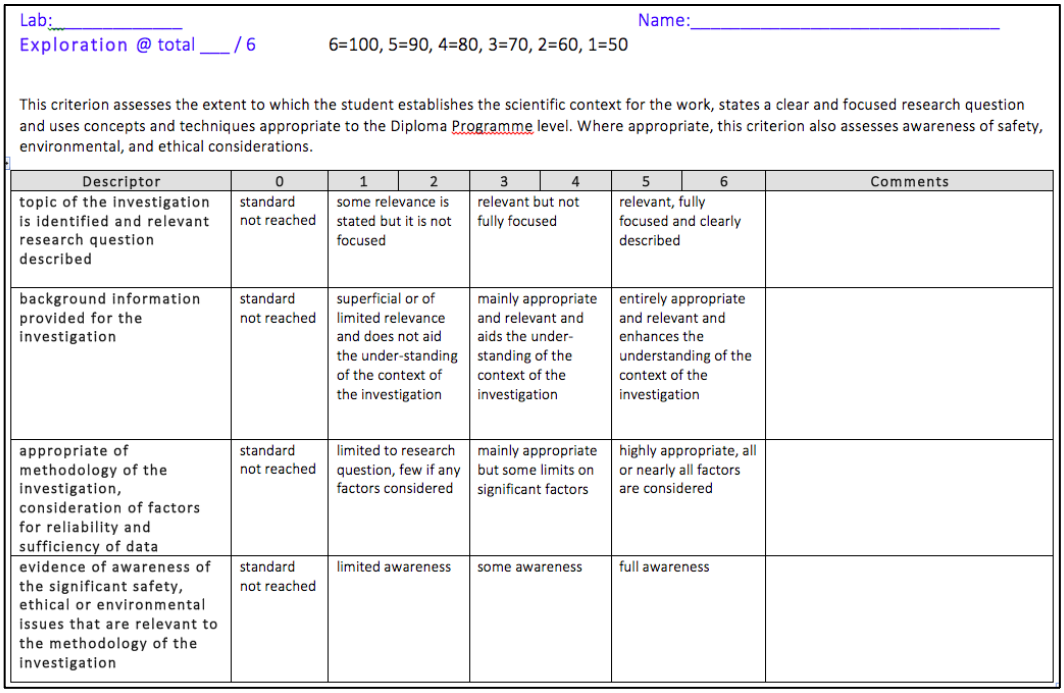
Leslie said she "loves how quiet she is in a day." I noticed it too. Sometimes she did not talk, allowing enormous wait times, leaving students to fill in the blank spaces when she refused. Some students hated it, especially right now, especially at first. Leslie knew that and she expected it after teaching this way for several years. When she first started teaching this way she used to commiserate with other like-minded teachers when students complained, even bringing teachers to tears with accusations of being an ineffective teacher. At times Leslie wondered, it would be easier to lecture, why don't I just lecture?! But she stuck with the open stuff because she remembered when she first started really learning physics—in college, after the formulaic answer-finding of high-school physics was over—and wanted students to experience that kind of learning. Then when she went to grad school she learned what it meant to "construct" knowledge and work in a zone of proximal development, and it made sense—hard mental work worked. Further, she needed to put kids there to get them to see that they were in charge of reasoning, and feel ownership over their learning. That would be more authentic to science, that would allow provide them with skills for understanding in new contexts, in any context!

> "We really found that kids walk into a classroom really expecting for you to just start throwing equations at them, and for it to be mathematics and

> science combined in a way that they don't really understand. I think that, unfortunately, a lot of science classrooms before they come to us, because they're so SOL driven, it's very much content, and they don't get to explore the general concept of what makes science science."

So Leslie watched her 6th period roll in the door and sit down. She let them read the board and get started only telling them, "You should be following number two on the warm up" which read, "List at least three examples of pendulums found in real life." She was going to try to connect this lesson on pattern finding to real life pendulum. Later in class, Leslie would be guide the students to investigate length of a pendulum and then ask them to declare a relationship they found from their investigation. After investigating multiple parts of a pendulum over several days, eventually they would make a composite understanding of how all the variables related, the pendulum equation, but they would have also practiced sense-making, pattern finding, predicting from evidence, and really doing *science* along the way.

Appendix 5.9: Leslie's Rubric for Open Inquiry



Lab:_____________ Name:______________________________

Exploration @ total ___ / 6 6=100, 5=90, 4=80, 3=70, 2=60, 1=50

This criterion assesses the extent to which the student establishes the scientific context for the work, states a clear and focused research question and uses concepts and techniques appropriate to the Diploma Programme level. Where appropriate, this criterion also assesses awareness of safety, environmental, and ethical considerations.

Descriptor	0	1	2	3	4	5	6	Comments
topic of the investigation is identified and relevant research question described	standard not reached	some relevance is stated but it is not focused		relevant but not fully focused		relevant, fully focused and clearly described		
background information provided for the investigation	standard not reached	superficial or of limited relevance and does not aid the under-standing of the context of the investigation		mainly appropriate and relevant and aids the under-standing of the context of the investigation		entirely appropriate and relevant and enhances the understanding of the context of the investigation		
appropriate of methodology of the investigation, consideration of factors for reliability and sufficiency of data	standard not reached	limited to research question, few if any factors considered		mainly appropriate but some limits on significant factors		highly appropriate, all or nearly all factors are considered		
evidence of awareness of the significant safety, ethical or environmental issues that are relevant to the methodology of the investigation	standard not reached	limited awareness		some awareness		full awareness		

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