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Teacher Productive Resources for Engineering Design Integration in High School Physics Instruction (Fundamental)

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Abstract

Recent reform efforts to embed engineering design instruction in K-12 science have provided an impetus for high school physics teachers to teach engineering design alongside content physics. This study, part of a larger participant observation dissertation study of engineering integration in high-school physics, investigated how a physics teacher, “Leslie,” integrated engineering design into a projectile motion lesson to address the question of how a physics teacher’s existing resources, or bits of knowledge and reasoning, help the teacher be productive in teaching engineering design in physics class. 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 may feel confused or overburdened with the engineering design reform effort may be able to draw upon their existing resources, especially those affiliated with inquiry instruction, to push through feelings of discomfort during engineering design instruction such as unexpected student divergence, requirements of engineering design processes, and time restrictions. Reform implementation researchers, teacher educators, and engineering professional development providers should also acknowledge the role that resources may play in reform implementation and encourage teachers to find and call upon resources they already have that align with engineering integration reform to help them out.

Introduction

“Leslie” heaved her lunch onto the table and dumped her body in a chair. (Pseudonyms are used throughout and Leslie chose her own pseudonym.) Usually excited during the school day, today she was wiped from teaching her first engineering design lesson, a self-planned engineering design challenge to build a catapult and teach free fall. All the mental work she’d been doing had drained her completely, and now she had 30 minutes to eat, regroup, talk about the lesson, and get ready to do it again after lunch.

Leslie started the year with no formal engineering experience but she was hungry for change and interested in integrating engineering design into her physics teaching. By the end of the year, after planning and teaching four engineering design challenges, Leslie was so gung-ho about engineering design that she volunteered to facilitate an engineering instruction professional development, and wound up transitioning into a full-time STEM coach role bringing engineering design to math and science teachers across a whole county.

But her growth wasn’t without some struggle. There were moments when it seemed like engineering design instruction might put both Leslie’s content and engineering design instructional goals in danger. By drawing variously on her pool of resources (or bits of reasoning) Leslie overcame unease in instructional moments and stuck with engineering design integration even when she felt confused, overwhelmed, or unsure. I found that Leslie activated some of the same resources in both engineering design instruction and inquiry-style facilitation in physics instruction. 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 for they find productive in other student-centered instruction, such as inquiry instruction, to draw upon in engineering design implementation.

Literature review and resources framework

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" (Evans, McNeil, & Beakley, 1990). It requires complex thinking, analysis (Katehi, Perason, Feder, & Committee on K-12 Engineering Education, 2009) and engineering mindsets (Katehi et al., 2009; Radaideh, Khalaf, Balawi, & Hitt, 2013) that are difficult to teach directly. In higher education, engineering design skills are developed through in-depth design courses taught separately from the bulk of engineering sciences courses. This bifurcation has been blamed for students and graduates who don't see connections between content math and science courses and engineering practice and careers (Froyd & Ohland, 2005).

As higher education continues to struggle with bifurcation the Next Generation Science Standards (NGSS) (NGSS Lead States, 2013) encouraged engineering design practices and science content to be learned simultaneously by K-12 students (Cunningham, Knight, Carlsen, & Kelly, 2007; National Research Council (U.S.), 2012; NGSS Lead States, 2013). Engineering design can then be a vehicle for learning engineering design and scientific content, emphasizing interdisciplinary, real-world applications and contexts of science (Douglas, Iversen, & Kalyandurg, 2004). But only 9% high school science teachers feel comfortable teaching engineering (Banilower et al., 2013) so combining engineering with the traditional and reform content demands in the NGSS may be difficult for high school science teachers.

The NGSS isn't instructive of curriculum or pedagogy; it doesn't 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. During authentic, student-centered engineering activities classrooms may feel chaotic or unorganized (Dare, Ellis, & Roehrig, 2014) and teachers themselves may feel uncomfortable (Katehi et al., 2009; Truesdell, 2014). To counter this unease, some external recommendations for how to teach engineering oversimplify engineering design thus reducing the fidelity of the design process in favor of creating easier to teach engineering design curriculum and to reduce teacher anxiety (see Douglas, Iversen, & Kalyandurg, 2004; Truesdell, 2014). Instead of doing the whole design cycle, including analysis, constraints, modeling, optimization, and trade-offs (Katehi et al., 2009), teachers may focus on variable testing only without a orienting the purpose of variable testing as a function of design (Dare et al., 2014), digressing to step-by-step processing (Dare et al., 2014; Holstein & Keene, 2013) or to trial and error (Dare et al., 2014). In practice, some teachers 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). In effect, recommendations that limit student choice and critical thinking to preserve the authority and comfort of the teacher may reduce the authenticity and impact of engineering design integration.

Though the NGSS encourages using engineering design to teach content, more typically identified methods of engineering integration in curriculum are: teaching engineering separately from science and math as a stand-alone course, i.e. Project Lead the Way (Katehi et al., 2009); using engineering as a culminating activity to use physics science concepts (Roehrig & Moore J., 2012); using engineering design to set up a context that can be typically solved by tinkering, not requiring new science content (Dare et al., 2014; Katehi et al., 2009; Roehrig & Moore J., 2012); engineering instruction devoid of experiment, where testing is not systematic, or allowing tinkering or trial and error to suffice in solving the problem (Dare et al., 2014); and teaching engineering concepts instead of science or math content like learning how to specify criteria and constraints (NGSS Lead States, 2013d), for example.

In sum, we haven't figured out quite how to advise K-12 teachers unfamiliar with engineering on how to teach engineering design alongside science content in the K-12 classroom. "As yet there is no clear description of the knowledge and skills needed [for] teaching engineering to children" (Katehi et al., 2009, p. 103) but we know that teachers will have to grapple with just what engineering design is; math and science content; the open-endedness of engineering instruction; deficit thinking about how their students would handle engineering design, and negative impressions their own ability to negotiate the complexity and demands of engineering design instruction with limited available time and resources (Douglas et al., 2004; Katehi et al., 2009).

In 9-12 science, physics might seem like a science with a high potential for successful integration because mechanical physics concepts and mechanical engineering seem so closely related (Dare et al., 2014). Physics teachers also have had more engineering coursework than other high school science teachers (28% to 10% respectively, (Banilower, 2013, p. 5)) but few studies focus on engineering integration in physics. Instead, most of the research on engineering integration so far comes from self-reporting or examining classroom and PD curricula, not watching classroom instruction or PD (Dare et al., 2014). This study answers the call for observational research on engineering integration in physics.

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. Briefly, I am considering resources to be bits of knowledge and reasoning involving 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, routines, and other bits of knowledge and reasoning that are activated based on context. For some, resources are of a finer grain size than beliefs and are sometimes described as analogous to diSessa's p-prims (Louca, Elby, Hammer, & Kagey, 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 framework states that 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.

In this paper I'm particularly interested in 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, but again, resources are not always consistently activated. This framework helps 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. Significantly, by seeking and documenting productive resources I am intentionally seeking affordances 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 warn off certain behaviors or decisions. It is my hope that using this assets-based framework will inform teacher PD in a more positive way than typical deficits-frameworks do.

Methods

In this qualitative study, I used ethnographic-like participant-observer methods (long duration observation, field notes, observation memos, analytic memos, and interviews) to become immersed in a three-person teaching team as a moderately active participant, maintaining a balance between participation and observation without taking on the full activities of the teachers (Spradley, 1980). I used ethnographic techniques to generate rich descriptions of the behaviors, and to "catch the diversity, variability, individuality, uniqueness, and spontaneity of social interaction" (Cohen, Manion, & Morrison, 2000, p. 139) in the case of high school physics instruction at Merlin. In the 2015-2016 school year, I observed 45 of teacher Leslie's 90-minute physics classes, about 67 hours of observation total divided among her three sections of on-grade-level physics, and conducted four hour-long formal interviews with her.

During observation, I used descriptive field notes and then synthesized my observations into rationales for action (Spradley, 1980). Simultaneously I employed tags in my field notes to note influencing resources (bits of reasoning) such as "foundations of science," "growth mindset," "bigger pictures," "creativity," and "student decides," among others. I narrowed to make more focused observations of engineering design planning and instruction, and during engineering instruction observation remained alerted to the same resources and kept notes in my field notes of when they appeared.

I began to identify some resources (bits of reasoning) as "productive" or seemingly activated in various moments and I found patterns of resources consistent in multiple instances. In focused observations of engineering design planning and instruction, and during engineering instruction observation, I remained alerted to the same resources and kept notes in my field notes of when they appeared. I made selective observations of Leslie towards the end of the school year looking for counterevidence to my growing claims about what sustained Leslie in moments of tension in her classes. After my analysis, I performed two member checks with Leslie, one in June and one in November.

Leslie emerged as singular in my sample for how her inquiry instruction resembled and seemed to support her engineering design instruction. (For a full discussion of the other teachers and characteristics of their engineering design instruction, see (Shirey, 2017).) Leslie did less directive teaching in various moments that caused the other teachers distress. When the others were distressed they tended to "lean in" and provide guidance or directions 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 authentic, student-centered engineering.

Over many months of observation of both her physics and engineering instruction, I realized that Leslie's physics inquiry instruction resembled and seemed to support her engineering design instruction, especially when she was nervous or in doubt. To write a story that encapsulated the significance of this realization, I returned to a time when Leslie struggled in engineering design instruction but persevered; her first day in the Pumpkin Chunkin' challenge. This paper focuses on that effort.

Limitations

My qualitative approach has several limitations. The sample size for this paper is one limiting the generalizability of my conclusions. I use descriptions of the data instead of abstractions of the data, which provides a detailed narrative, but limits the ability of the reader to draw their own conclusions. My experience as an embedded participant observer with Leslie over a whole year increased my familiarity with her so my assumed understandings of her pose a threat to validity and may sounds as if they are my own opinions. To counter this threat, I conducted two formal member checks and six informal member checks with her.

Positionality Statement

I walked a line between teacher-collaborator and engineering integration expert as I observed and worked with Leslie. After teaching, observing and evaluating student teachers for several years, I have no doubt that my observations and analysis were influenced at least in part by my experiences teaching and supervising student teachers, and it's 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've studied physics and sculpture and believe that making involves learning just as I think teaching requires learning, too. It is likely that exploring similar constructivist epistemological stances in myself influenced even my interest in engineering, and certainly my interest in Leslie.

Productive resources in Leslie's inquiry instruction

Some of Leslie's physics instruction resources helped when she tried engineering design instruction for the first time, particularly ones that related to her inquiry instruction in physics. Inquiry instruction, or inquiry-based instruction (Supovitz, Mayer, & Kahle, 2000), refers to a mode of instruction and constructivist learning (Abd-El-Khalick et al., 2004) in which teachers provide opportunities for students to learn classroom science concepts through extended investigations with phenomenon before they are told the science content rules, definitions, or relationships. With roots in Deweyan Project Method in the mid-20th Century and emphasized more recently in the National Science Education Standards in 1995 (Czerniak & Lumpe, 1996), inquiry instruction gets its name from "scientific inquiry." Inquiry instruction can provide students with opportunities to take on the authority of their own learning, to make decisions about what to learn about and why, and to behave more like real scientists than usual didactic instruction allows (Czerniak & Lumpe, 1996; National Research Council, 1996).

Inquiry instruction can involve more or less guidance from the teacher, but the most open inquiry involves no teacher direction. During inquiry instruction teachers must allow students to make decisions, test hunches, and at times, fail with minimal intervention (Kirschner, Sweller, & Clark, 2006) to reduce students' reliance on the teacher approval or knowledge. Teachers like Leslie, who use inquiry instruction, must have a host of inquiry facilitation resources that they draw upon when facilitating inquiry to ensure that students are working independently but achieving something meaningful, too. Inquiry-based instructional moves include providing minimal teacher guidance, setting up opportunities, emphasizing conclusions drawn from laboratory work, and scaffolding student self-guidance.

After observing 45 of Leslie's classes, the inquiry resources that I found in her most authentic engineering design instruction were: not giving away steps or instructions in experimentation; requiring that students take good-quality data and use pattern-based reasoning to make sense of a phenomenon; giving up teacher authority to increase student-centeredness; holding constructivist and social constructivist stances for learning; believing learning can come from indirect contexts; and a growth mindset. I will discuss each of these briefly as they appeared in her non-engineering instruction before identifying them in Leslie's Pumpkin Chunkin' challenge.

<u>Leslie required student reasoning by not giving away the steps.</u> Leslie reported that when she was in high school she "was taught very formulaic ways of getting to answers" using very few labs and correct problem-solving steps. In contrast, Leslie did not teach students formulaic ways of getting to answers. She answered student questions with questions demanding that her students reason for themselves instead of relying on her reasoning. She rarely told a student what to do next, instead of requiring the students to consider their goals and possibilities on their own.

<u>Good data and pattern recognition</u>. Instead of teaching rote relationships by equations, Leslie used inquiry to teach relationships empirically, using no less than 12 labs to teach new relationships before discussing the targeted formula. In this inquiry instruction, Leslie required that students make sense of their data using mathematical pattern recognition, and so she wanted students to use appropriate empirical techniques to gather lots of high-quality data because then she could trust that the relationships would emerge. She consistently reminded students to rely on their data and to not be burdened by their preconceptions for a relationship. Leslie provided time for students to make sense of observations, sometimes sacrificing an extra example or an extra comment so they could continue working. It takes longer to teach this way, but Leslie was willing to give up precious time to teach this longer, student sense-making learning way.

<u>Leslie gave up teacher authority to help increase student-centeredness.</u> Leslie's classroom environment simmered and hummed without her having to be in obvious control. Leslie was actively quiet, listening for tens of minutes, sometimes up to thirty minutes or more without interrupting student work. Leslie estimated, and I concur based on my observations, that she spent only up to one-sixth of her instructional time talking directly to the students. When necessary she could assist in pushing a group along, but she seemed to prefer that students had

the authority to make decisions in the class. 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."

Leslie was purposefully not the judge and arbiter of success, but students were not left without help: Leslie used tools such as peer-reasoning check-ins, technical resource sheets, small group demonstrations, rubrics, and group collaborative so that she was not required to provide approval or primary instruction during inquiry explorations. Turning sense-making over to students required that students solidify information on their own, reducing the amount of top-down control of the teacher. Effectively, these tools freed up Leslie in the lab space; Leslie didn't have to run from group to group assisting each group individually. Her attention to the whole room and the larger task of inquiry overall could be wider than if she were narrowed in on helping individual groups.

<u>Leslie held a constructivist stance in inquiry instruction.</u> I believe that Leslie desired students work with data from empirical observation and withheld giving away the steps because Leslie thinks learning happens when students construct understandings from experiences, communication, and reflection, indicating a constructivist learning stance. A constructivist stance is made up of many smaller reasoning resources including perhaps, "knowledge is constructed not given" and others. Leslie seemed to call up the constructivist stance very readily, so here I'm treating it as a compound resource in its own right instead of trying to unpack it down to its many minutiae. And sure, at times other stances seemed to dominate, but frequently in inquiry instruction, Leslie seemed to have a strongly constructivist stance.

<u>Social constructivist stance</u>. Student groups were at the heart of Leslie's class and she really made it clear that the whole group mattered: she scaffolded group norms that valued all contributions such as group consensus and asking for differing opinions. Teams were all accountable to one another before they were accountable to her. 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 knowledge is created by many people together. This reveals a very social constructivist stance, that literally the knowledge forms and emerges as students reason together, out loud about a phenomenon they are seeing.

<u>Learning can come from indirect contexts.</u> Leslie seemed to believe that learning physics was aided by bringing in examples from non-traditional realms for students to learn from and apply their learning to. For instance, she used the judicial system to help support the importance of communicating claims, and Mars rovers to contextualize about vector addition. She encouraged her students to "Have adventures! Make good choices!" when they left her classroom on Fridays. It seemed that Leslie believed construction, transfer, and learning were increased when the content was framed in rich, even if sometimes indirect, contexts.

<u>A growth mindset where failure is productive.</u> Leslie followed some practices that indicated she had a growth mindset towards learning: she believed that ability in physics, in teaching, and in general learning can be developed, she actively embraced failure as a way to learn. Not only did she allow students to remediate poor tests and quizzes in all of her classes, and use a standards-

based grading method in her IB physics classes, she spoke about failure as a way forward, 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 saying "Puzzle it out" pointed to her appreciation for the struggle that students are going through as they learn and her conscious effort to keep them interrogating the answers they may arrive to.

Table 1 summarizes Leslie's inquiry-based instructional resources that were also helpful in her engineering design instruction. Not providing direct answers, requiring student autonomy and sense-making ties directly to open scientific inquiry instruction (Rezba, Auldridge, Rhea, & The Virginia Department of Education Office of Elementary and Middle School Instructional Services, 1998). For Leslie, inquiry instruction in physics required 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.

Leslie's Inquiry Instruction Resources
Leslie did not tell students the steps
Leslie valued good data and student pattern recognition
Leslie gave up teacher authority to help increase student-centeredness.
Constructivist: learning occurs when knowledge is constructed by students
Leslie valued students' social construction of knowledge.
Leslie valued learning in contexts, even indirect ones.
Leslie valued failure as productive for learning.

Table 1. Leslie's inquiry-based instructional resources

Leslie's favorite inquiry memory exemplified how Leslie allowed exciting student engagement and discovery by stepping back. 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 put out--a way to measure caloric energy stored within the material. Some teachers might have heard or seen that research idea from a student, "I want to light it on fire," 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 their responsibility to justify conclusions using claim, evidence, and reasoning formatting. This example shows how Leslie relied on data to promote good reasoning, resisted providing steps, gave authority to students, and provided space for knowledge to be constructed. Leslie frequently referred to this "lighting spaghetti on fire" moment as shorthand for students doing meaningful, independent, scientific inquiry.

Leslie's Pumpkin Chunkin' engineering design challenge

Leslie crafted an engineering design challenge based on an annual event in Delaware, the Pumpkin Chunkin,' which involves competitors shooting pumpkins for distance or accuracy using catapults, trebuchets, and air cannons. Leslie introduced the challenge to her students by showing two videos in which participants in the real event described the event's requirements, then she asked them to come up with their own team problem statement, gave them a scaleddown starting apparatus (a popsicle stick catapult) and asked them to improve upon the design to reach their team's goals. To prove their success they had to document their team's candy-pumpkin flight path and find the accelerations in both x and y directions. Leslie's physics content goal was that they would better understand the accelerations of parabolic motion and free fall. Her engineering content goal was that the students would do problem definition, design optimization, and design communication via a written statement and competition in a final contest.

As Leslie's planned and instructed her Pumpkin Chunkin' engineering design challenge she ran into moments that caused Leslie to question how she was teaching engineering design. Before instruction, she feared, what if students were going too wild? What if she was teaching it wrong? During instruction, she encountered tensions over time demands, surprising student divergent thinking, issues of authority, and how to really draw out physics content during the engineering challenge without being didactic. Leslie called upon the resources she used in inquiry facilitation to help her get past those concerns to facilitate a student-centered engineering design challenge.

Providing a blow-by-blow account of the whole class is beyond the scope of this paper. Instead, I have identified within her first attempt at this lesson some moments where Leslie pushed past feelings of tensions by calling up her preexisting resources. This narrative will zoom through pieces of the lesson chronologically but pause on key moments of tension in order to pay attention to the resources Leslie activated and draw out the productive inquiry resources she called upon. When Leslie was most nervous and agitated, the resources she called forward helped her redirect students, to stop herself in mid-sentence and take a different tack, and to persist with the lesson. At lunch after her first exhausting attempt, Leslie and I spoke about how she should trust her inquiry instruction instincts instead of fearing that she might be "doing it wrong." Our conversation proved pivotal; following that conversation, Leslie had more enjoyable second and third tries wherein she didn't seem as worried about getting it right, and instead let her "good" resources play out in support of engineering design.

To be clear this was not an elite engineering class. Sure, it was a pretty prestigious school but this class was not AP, or IB or even honors Physics. It was general physics for students considered on or below grade-level in math. This class wouldn't have a standardized test at the end of the year so sometimes students who wanted a science credit but don't want to risk the science credit on test performance took it. This period usually contained a full range of engaged and unengaged students, a dozen or so students with accommodations, and plenty of chatty students. Again, this wasn't some magical class, and it wasn't even Leslie's most docile class of the year, this was a class of high school juniors and seniors about to go on a journey into engineering design.

"As engineers"

Leslie used the context of the real Pumpkin Chunkin' event to contextualize the parabolic motion they would study. 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 that they'd be designing a machine to compete in the Chunkin' but they could design it for anyone, a Chunker, an investor, a student, themselves, or anyone else they could dream up. Based on that client, they would need to decide what their goal was "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, with an emphatic pause after. Leslie doubly-contextualized the learning event: they would be using the real context of the Pumpkin Chunkin’ but they would also be assuming an engineering role for a hypothetical client (but not her).

Leslie signaled that there would be a tool to help them: “I’m going to pass out a packet to think our way through this.” Leslie handed out a document with boxes and words on the front. 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 told them, “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 didn’t stunt the class’s excitement by making students listen quietly while she went over the worksheet. By providing a tool she could step back and the tool carried authority for what should happen next, not her.

The boxes on the paper were laced with new engineering vocabulary like “criteria,” “constraint,” “stakeholder,” and “problem statement,” but she did not even stop to define these vocab words. Instead, she threw the responsibility of reasoning through what the prompts 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 played while students negotiated with the understandings they already had of those words, not from her describing 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. This was consistent with her constructivism and social constructivism resources in inquiry instruction: the students were drawing on their individual and collective experiences to construct new understandings about the use of this language in this context.

By this day in late November, a culture of student talk was pretty 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 in the back flagged Leslie down for a question: “Ms. [Leslie]? Are we focusing on distance or accuracy today?” In inquiry instruction, Leslie normally wouldn’t answer this sort of question outright with a straight answer, especially not after she told the students to puzzle out this exact question in their groups (she had just said, “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’d done this engineering design thing. What if they couldn’t articulate the problem? What if there were too many options and they couldn’t focus in on what the challenge required? What if she hadn’t provided them an adequate introduction? Here was her first moment of doubt: She intended for them to be able to state the problem in their own words so they’d get invested in it, but she also didn’t want them wandering off the path she was planning for--this was a lesson on projectile motion and 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 to 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 didn't really come to a single answer but Leslie didn't have a single answer in her head. For Leslie it would have been fine if he'd said, we're supposed to 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. That reasoning and engagement were 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, buy-in, authority and reasoning high.

Next students shared their responses and Leslie led them through a refinement of the vocabulary, specifically "criteria" and "constraints." Leslie stiffened when she said, "I'm going to talk to you about the difference between these two words 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. In this case, the students had already laid out some criteria and constraints before giving formal definitions, much like students using some relationship in an inquiry lab before explicitly teaching the formula.

At lunch, Leslie and I talked about this. She again said she had been intimidated about getting it 'right' during class, so even though she knew they could use it, she felt a responsibility to some higher engineering fidelity. She said 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?'" In my perception, 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 the "rules." Luckily, she remembered her teaching instincts. Like in her other physics teaching, she asked the students to do their own sense-making before going over the formal definitions. In the moment when she was nervous, she pulled from her inquiry resources pertaining to student sense-making to prevent the lesson from becoming a lecture.

Next students continued to use the tool to create a scaffolded refined problem statement. They had to use 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 out their refined problem statements. The variety of scenarios and stakeholders chosen was broad. A few groups said they were building their catapults for Leslie, and a few said for the students themselves, but some defined unlikely and even fictitious stakeholders: for Jack Skellington the

Pumpkin King from the Nightmare Before Christmas movie, for Soviet Russia (a time-period catapult), for the U.S. military, etc.

As they shared out Leslie nodded and said: “good, good, okay next” seemingly rushing them along. Leslie was listening and encouraging while withholding judgment but 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 shared their ideas she was worried that they might be doing the engineering design wrong, she wasn’t sure. Were the problem statements adequate? she worried. 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 ways that she presented the problem? Did it make the challenge weaker overall? Leslie reflected, “That's why it feels so uncomfortable is because there's actually a ton of freedom in this project.”

So how did she get past that discomfort of wanting to make sure they were doing it right? In the moment she pulled from inquiry resources such as student-centeredness, the utility of contexts and acceptance of risk leading to growth and respected their choices. She didn’t 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’d interact with a catapult to capture free fall and that would be valuable.

Design Exploration, Testing

After the students shared out their refined problem statements, Leslie’s attitude eased. Leslie explained that she had tried many, many catapult designs at home and that she chose this one for them to optimize. That was sort of a lie; she’d chosen this design to improve because it gave them somewhere to start and offered many potential ways to change it. They would need to take data to justify their “best” design. When Leslie passed out a model of the starting design the energy in the room totally shifted: students were jazzed to touch the models. As students flicked the spoon back, others instinctively reached in to hold down the base. They didn’t 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 clarified “optimize” or “optimization” yet.)

Leslie was comfortable with allowing the groups to design their own optimization procedure, just like in an inquiry investigation. Even still, Leslie had assumptions about how the data collection should go: The students were going to design an improved catapult but they had to test just one variable at a time, and if they did then at least the testing would make logical sense. This reflected her inquiry resource that good data will lead to good pattern recognition.

The energy in the room grew into a frenzy. The models had centimeters marked out along the arms to suggest a scale, but soon students began to modify their apparatus in fast fits and starts as they played around to decide on a variable to change. There was no formal hypothesis. Instead, the students were reasoning quickly and interacting with the apparatus to rapidly play out some of their hunches about what might work. One group was interested in making a much, much longer lever arm so they were experimenting with taping and rubber banding 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. This exploration looked like what might be called tinkering or rapid prototyping.

"Total chaos"
I saw Leslie looking around the room at all this tinkering in a tempered panic. Her eyes were wide as she watched them. They weren't 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 the long lever arm, removed from the stack, that went flying as someone whacked one end of it. Leslie scanned the room and surveyed all of these things happening at once. Later, Leslie remembered this part of the lesson vividly, saying, "I was really wigged out by what was happening. It was total chaos." In this moment, again, Leslie was worried that somehow she and the kids were doing it wrong. At lunch, she said, "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? Are they not realizing something that I should be making them realize? Are they 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?'"

Normally in her physics inquiry labs, Leslie allows wild ideas but here in engineering, she was worried because she wasn't sure if her natural inclination to let the kids "go free" would help them learn about projectile motion and the engineering design process. She wasn't sure that the students were following appropriate engineering conventions, so she couldn't be certain if they were going free within sight of good engineering design or not. But in the moment, Leslie's inquiry resources prevailed allowing student choice to override everything, even wrong answers, as long as the appropriate analogous scientific inquiry conventions were followed. It was Leslie's faith in student construction of knowledge through seeing, doing, and reasoning that got her through the stress. Instead of limiting the student designs, she allowed it to go on, even though she was nervous. So though her eyes were wide with fear, Leslie maintained her usual classroom facilitation stance: she watched, answered questions with questions, and let the students stay firmly behind the wheel of the ship. Leslie wasn't certain where exactly the ship should be headed, but she knew the students should be at the helm so she left them there.

Even in the midst of the chaos, Leslie's dedication to good data emerged as another resource for keeping her calm. When Leslie noticed many variables changing at once she did not jump in to redirect the students, instead, she conferenced with me hopefully, "They are diverging widely but might just be realizing that it's hard to keep any variables constant." And when she came upon a group making decisions about their design based on conjecture only she relied on her data and reasoning resources, 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 many responsibilities in the lab: requiring repeatability, controls, adequate trials, etc. She didn't need to stop their divergence to get them back to the work of co-constructing knowledge from doing, she just needed to remind them to use their data collection and pattern recognition skills to make their optimization more justified.

When she approached the group who removed the long lever arm from the initial apparatus she found that they wanted to change the position of their fulcrum, and that seemed adequate for her data and reasoning requirements, so she did not intervene even though she felt like they might have been violating some rules in the brief. After all, the brief said “revise this catapult design” not “demolish and ignore this catapult design.” Even though she wasn’t sure if it was “allowed,” Leslie still didn’t disrupt their process. Later she told me that she was going to use this example to discuss the authority and specificity of the design brief and to discuss reliability in a designed product. But at the time, she just stared on, as they met her minimum experimental data requirements and continued to work on their design without her intervention.

One group’s data was coming out in a way they hadn’t expected, and Leslie took the opportunity to remind them about relying on the data and pattern recognition. The student approached Leslie and said, "Miss [Leslie], my last data point is lower than the one before it, but it’s supposed to be linear." Later 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, ‘Whaaaat.’ And I was like, ‘Go!’ We didn’t talk about peaking!” Leslie recalled this interaction with a smile. “I just am excited for them to see meaning in their data.”

As time ticked down Leslie began to panic about project completion, “Okay there’s only seven more minutes [until the launch test], you all need to finish taking your data, emergency style!” Leslie’s plan for a complete data set was under threat. She’d been relying on her good data leads to good reasoning and learning resources, 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 wouldn’t be able to recreate-- if the apparatus were dismantled it was unlikely that they’d have the exact same materials and conditions when they returned to her class in 48 hours. Instead of compromising on the work, letting them gather less data, or providing them another way out, Leslie insisted they get it done. It took them until the very last minutes of class, and then Leslie called everyone out to the hallway for the first ever Pumpkin Chunkin’ Prototype Competition. The launch scene was joyous with candy pumpkins flying, kids laughing and arguing about who landed where, pumpkins bouncing off the ceiling, lockers, kids, and the floor. The winning team was the detached arm team and they received candy pumpkins to eat or to share.

Immediately after this class at lunch, Leslie was beat. In explaining that her fatigue she said she’d been doing mental work during the challenge because she’d been stressed about teaching engineering design wrong, or them doing engineering design wrong. She was further stressed by my presence because she ascribed me some 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, ‘Ok, 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 is 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 or repeated creations. Very similar creations. And even with 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 had felt insecure about what was right because she too was a novice with the engineering design process. She knew they would have multiple outcomes, but over and over wondered if her students were doing it correctly and if the divergent chaos was okay. And yet, even though she was negotiating this stress she got past it to continue in the lesson by calling up her confidence in good data, student reasoning, student teams and constructivist stances.

Summary: What productive resources got her through this?

Leslie ran into a tension with her assumption of some concrete understanding of what's acceptable for engineering design. This tension made her feel stress and exhaustion, feelings that could have led her to give up on the challenge, abandon the open-endedness of it, or not do it again. But when teaching, a host of resources came together, as they did when she's teaching physics, to help Leslie continue her engineering design instruction in a more authentic way, instead of removing student agency or saying "this is engineering design and here's how to solve your problem."

Leslie called upon many inquiry instruction resources such as creating context, believing in good data and pattern recognition, and the importance of group consensus (see Table 2). Students thought far and wide, and Leslie encouraged them without giving away what she might prefer or think was correct. She withheld judgment, required and respected student choices. I saw evidence of various resources cohering as well, such as Leslie not giving away the steps combining with a social constructivist stance and the resource that productive struggle is learning. Instead, she put authority on external tools and on the students themselves. She used her inquiry facilitator resources to push the engineering design agenda forward even though the engineering process was stressful.

Although she expressed concern about the Pumpkin Chunkin' 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 more comfortable with engineering, Leslie described the experience as fun. "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?"

Discussion

That physics instructional 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 some wrong and right ways to design, some limits to the options that could be explored other than the problem's scope. Leslie may still be developing her understandings of engineering design, but she was able to help students complete the divergent activity she planned for.

Leslie's Inquiry Instruction Resources	Inquiry Instruction Resources Productive in Leslie's Engineering Design Instruction
Leslie did not tell students the steps.	Leslie required students to develop a purpose on their own.
Leslie valued good data and student pattern recognition for content learning	Leslie focused students on taking enough data to demonstrate a pattern even when it seemed chaotic, "Go with what your data tells you."
Leslie gave up teacher authority to help increase student-centeredness.	Leslie allowed students to devise their own procedures at their own pace, even though she was distressed at the moment.
Constructivist stance: learning occurs when knowledge is constructed by students	Leslie scaffolded student use of "criteria" and "constraint" appropriately without having to first define them. The challenge could teach students the arc of a projectile in free fall without direct instruction.
Leslie valued students' social construction of knowledge.	Leslie required student groups ask one another for confirmation, not her.
Leslie valued learning in contexts, even indirect ones.	Leslie positioned students as fictitious engineers for the real Pumpkin Chunkin' context
Leslie valued failure as productive for learning.	Leslie allowed the long lever arm group to proceed even though she recognized they would run into trouble with reliability and hadn't anticipated their approach.

Table 2. Leslie's inquiry instruction resources related to her engineering design instruction

Leslie's inquiry-associated physics teaching resources came back, again and again, to assist her in engineering design facilitation to put her back on "safe ground" when she worried she was doing it wrong, or even when the lesson felt like it was shifting into total chaos. In future challenges, these resources remained helpful. For instance, when she was worried about data collection skills in a parachute design challenge she relied on a well-designed technical resource sheet to stay agile in the lab space. And when students wanted to improve a cell phone case by changing its color she insisted they use good data to justify their design decisions.

Conclusions and future directions

High school physics is considered a "prime target" (Dare et al., 2014, p.48) for engineering design integration offering a "relatively mild transition" for teachers (Dare et al., 2014, p.49). But even the best-intentioned physics teacher may face difficulty trying to bring authentic or "correct" engineering design practices and problems into physics class in a way that also provides opportunities for learning physics content.

In this study, Leslie encountered 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 including the value of productive struggle. Seeing what her brand of engineering design instruction looked like, with embedded content physics practice and content acquisition helps to operationalize the NGSS for high school science instruction. Teachers may be encouraged to seek the resources that assist them in negotiating student-centered instruction and attempt to pull from those in engineering design instruction, or they may be interested in working on developing some of Leslie's resources described here.

Very student-led open inquiry instruction (Bell, Smetana, & Binns, 2005; Rezba et al., 1998) 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), but little research acknowledges the connection. The connection between engineering design and self-guided inquiry is an area still in need of research. Indeed, the Committee on K-12 Engineering Education concurs, "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 affiliation between inquiry and engineering design seems especially productive to me as a teacher educator and professional support provider of math 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 inquiry facilitation resources. Further work across more engineering challenges, contexts, and teachers will be required to say if there is a definite relationship, though this study seems to indicate that at least for Leslie inquiry resources were also productive in engineering design.

Similarly, this paper opens a discussion for whether Leslie's productive resources were recurrent or cohesive her other instructional settings, and how those formations and activations changed over time. Further investigation of Leslie's use of engineering design over the whole school year could begin to describe how her first year of engineering integration looked, not just her first try at engineering. Such research might be instructive for coaching science teachers and they integrate engineering.

Leslie's interest in "fun" 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.

The NGSS implies that engineering design can teach science content. In this lesson, Leslie's free fall content goals were very important to her. However, this paper's analysis does not go into content attainment from the student or teacher perspective. Further work should be done to assess the success of this lesson in teaching free fall content.

While for Leslie, these particular resources proved especially useful, other inquiry instruction resources may also be useful for engineering design integration in science. Further research is necessary to investigate if that is the case, however, based on this analysis, professional development providers and teacher trainers should encourage teachers to draw on their existing inquiry instruction resources instead of becoming caught up in getting engineering exactly right.