Integrating Engineering into Core Science Instruction: Translating NGSS Principles into Practice through Iterative Curriculum Design

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Abstract: *The Next Generation Science Standards now integrate science and engineering through their Core Ideas and Practices dimensions. Portions of the engineering design process included in these standards emphasize: 1) defining problems through identifying criteria and constraints, 2) developing solutions to those problems, and 3) optimizing those solutions to best fit the criteria and constraints. The Science Learning Integrating Design, Engineering, and Robotics (SLIDER) project, funded through the NSF DRK-12 program for five years, set out to investigate this integration through the use of robotics and design to develop conceptual understanding among 8th grade physical science students. Through three years of curriculum development and iteration, the SLIDER curriculum faced several challenges in making this integrated approach both effective and practical in a diverse array of schools. This paper presents that story and makes suggestions critical to others designing for the NGSS and developing theory around integrated STEM learning.*

Keywords: science education; engineering education; design; integrated STEM; curriculum development; Next Generation Science Standards

1. Introduction

The *Framework for K-12 Science Education* [1], published by the National Research Council in 2012, proposed certain elements of engineering as central to a thorough science education. These core engineering ideas - namely the Engineering Design Process (EDP) and Links Among Engineering, Technology, Science and Society (Links) - were then woven into the Next Generation Science Standards (NGSS), published in 2013. The EDP [2] NGSS standards emphasize the following: 1) defining problems through identifying criteria and constraints, 2) developing solutions to those problems, and 3) optimizing those solutions to best fit the criteria and constraints. The Links standard encourages real world contexts to foster engagement and understanding of science. It is now the responsibility of curriculum developers and classroom teachers to determine how these additional concepts can be included in what is universally acknowledged to be an already tightly filled science educational domain. The solution generally proposed is to integrate the science and engineering [3].

Science Learning Integrating Design, Engineering, and Robotics (SLIDER) is an NSF-funded DRK-12 project that is investigating this integration. SLIDER set out in 2010 to examine the use of design and engineering, via robotics, to develop conceptual understanding and skills among 8th grade physical science students. The SLIDER curriculum was built upon the research and curriculum developed in the NSF-supported *Learning By Design*™ (LBD) project, which featured the use of design challenges and project-based learning to facilitate science learning [4]. In curriculum units ranging from 2 to 4 weeks, LBD students iteratively proposed and developed solutions to a problem in inquiry-based, project-based middle school science classrooms. The purpose was to explicitly learn science concepts, develop in students the skills and practices of scientists, and, perhaps to a more limited degree, engage students in engineering processes and concepts. The SLIDER project adapted LBD's curricular approach and set out to explore the promise of using robotics and design more prominently in these types of learning experiences and to investigate their effects and affordances for learning science.

From 2010-2015, the SLIDER team iteratively developed and tested curriculum units that incorporated LEGO NXT Mindstorm™ robotics and LBD-like engineering contexts. In SLIDER, 8th grade students develop understanding of energy, motion, and forces as they engineer a solution to an authentic traffic accident problem by designing 1) traffic rules for a dangerous intersection, and 2) an automatic braking system for a robotic LEGO truck. Even in the early version of the SLIDER curriculum, students defined the problem, iteratively designed possible solutions, and ultimately settled on a solution. Midway through the project, however, the release of the NGSS Frameworks made the integration of some science and engineering practices more explicit and provided SLIDER with a more definitive theoretical foundation. This paper will detail the SLIDER project's curriculum development as the project attempted to navigate the newest goals the NGSS presents for science learning. Through four years of iteration and testing, the use of robotics in the curriculum changed significantly. And thus, the engineering experience changed with it.

2. Background

The SLIDER team designed the curriculum units employing backwards design principles [5]. The most important goal was that the curriculum's activities and classroom materials had to enable students to learn physical science disciplinary concepts and science practices. Other primary intentions were to use engineering contexts to drive engagement and provide iterative application of conceptual knowledge, to infuse physical science with practices drawn from the field of engineering design, and to use LEGO NXT robotics as the manipulative and tool.

As the team first conceived the curriculum, it saw great opportunity and affordances to LEGO's NXT robotics kits. Students obviously could build artifacts or products as they would build a play toy or model. The kits also offered students the ability to program the LEGO robot to move within and react to its environment, thus allowing the robotic device to become an engineered product. We imagined students designing, testing, analyzing, re-designing, re-building, and re-testing many aspects of the model truck featured in our curriculum's design challenge. This could include the chassis, the wheel and tire assemblies, the design of the brake arm, and even the program that runs the sensors activated during a potential collision.

Furthermore, the kit's sensors embodied a number of concepts in physical science. The sensors use ultrasound, audible sound, changes in light, reflection, touch sensing, and infrared. We saw an opportunity to use these sensors to make more explicit topics like waves, electricity, energy, light, and sound, which have historically been difficult for middle school students to grasp [6].

Based on the team's previous experience with established extra and co-curricular K-12 robotics programs (e.g., FIRST LEGO League, and the use of LEGO NXT kits in engineering and technology classes), we hypothesized that situating physical science learning within engineering design scenarios where students design LEGO NXT robots to solve specific challenges would increase student engagement, motivation, and achievement--a proposition suggested or supported by existing literature [7-13].

2.1 Integrating Science and Engineering

Integrated STEM learning has gained traction in public policy imperatives and is currently talked about in the national media as one possible way to address our national STEM education challenges. The concept of integrating science and engineering concepts in order to promote student learning is certainly not new. Both Kolodner et al. and Fortus et al. have reported on the effectiveness of curricula that use engineering concepts and engineering design to teach middle school science [4, 14].

From the beginning, SLIDER intended students to move in and out of engineering concepts and activities during the course of its 3-4 week units. In particular, we incorporated the engineering concepts later articulated in the NGSS: defining problems, proposing solutions, and optimizing solutions. The central challenge posed within the curriculum plays a key role, as it is the context that situates the learners, drives purpose and activity, and allows for both science and engineering learning to occur in the same class. SLIDER units can be characterized as STEM-design challenges per Berland's differentiation between STEM-based, problem-based, and engineering-based challenges in that the goal of the unit is to learn both science and engineering [15]. How this interplay between the science and engineering design plays out through the curriculum, and the nature of the learning that takes place, were central questions for the SLIDER team. The National Research Council (NRC) provided a starting point and theoretical underpinnings regarding the notions of infusion vs. mapping of engineering and science concepts and about approaches to curriculum design and inquiry.

2.2 Infusion vs. Mapping

The *Framework for K-12 Science Education* explicitly included engineering practices and core concepts within the domain of science education, and the NGSS made explicit that science teachers should include engineering concepts alongside the scientific ones. How this is to be achieved was not defined by the NGSS, though the NRC had noted the issue in previous publications. In 2010, the NRC had published *Standards for K-12 Engineering Education?*, which examined the nature and concept of potential K-12 engineering standards [3]. That report, as well as the NRC's report on *STEM Integration in K-12 Education* [16], emphasized the current lack of understanding about how STEM integration should be executed, and included recommendations that future research explore the synergies between the STEM topics and how materials should be designed to engage all learners.

The *Standards for K-12 Engineering Education?* report considered two approaches for integrating science and engineering standards in the same classroom: *Infusion* and *Mapping*. The difference between them is not stark, but they are unique approaches. Consider the analogy of viewing standards as puzzle pieces that form a picture of desired learning outcomes. Infusion is the teaching and learning of separate standards as if they were separate puzzle pieces. The pieces would maintain distinct boundaries and contain unique portions of the overall picture, either as science or as engineering. They would be taught separately, but sequenced in a logical manner and have the ability to lock with other pieces. In more practical terms, students would learn about science and engineering separately and then find out how those concepts might fit together. In Mapping, imagine two puzzle pieces, one from science and one from engineering, that look and fit into the puzzle similarly (e.g. designing and running experiments in science and designing and conducting tests of prototypes in engineering). In Mapping, there is enough overlap in those two skills that the two can be taught concurrently and somewhat interchangeably.

The *Framework for K-12 Science Education* and Bybee make the case that science and engineering essentially share eight common practices [1, 17]. Of the eight, only two—1) Asking Questions and Defining Problems, and 2) Constructing Explanations and Designing Solutions—are significantly different between science and engineering. This suggests that six of the eight core practices—Developing and Using Models; Planning and Carrying Out Investigations; Analyzing and Interpreting Data; Using Math and Computational Thinking; Engaging in Argument from Evidence; and Obtaining, Evaluating and Communicating Information--can be effectively mapped together, whereas for the other two, care must be taken if the learning goals for both disciplines are to be effectively covered. In these cases, those learning goals are being infused into the science curriculum.

The NRC's conception of the specific engineering concepts that should be included in science education are made explicit in the NGSS and listed as Disciplinary Core Ideas, ETS1.A, ETS1.B, and ETS1.C. [2, APPX I, pp. 1]:

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

These defined standards provided SLIDER with specific engineering learning goals. The challenge became how to best integrate them within the science curriculum, either through mapping or infusion, and how to do it in a way that maintained the levels of scientific inquiry recommended through educational research.

2.3 Curriculum Design and Inquiry

In addition to determining how science and engineering would share space in the science classroom, SLIDER was dedicated to maintaining best practices for teaching science. After all, the primary focus of the Physical Science course is to learn physical science concepts. Bransford et al.'s How People Learn provides clear rationale and guidance for the NRC's 1996 science standards, for the new NGSS and for designing inquiry-based learning experiences [18, 19]. While specific methods of inquiry learning are not prescribed, experiential learning in science curricula is at the very least viewed as good practice, if not best practice. Inquiry, though, does occur in several formats, and Banchi and Bell's *Many Levels of Inquiry* illustrates this idea [20, pp. 27].

1. *Confirmation Inquiry—Students confirm a principle through an activity when the results are known in advance.*
2. *Structured Inquiry—Students investigate a teacher-presented question through a prescribed procedure.*
3. *Guided Inquiry—Students investigate a teacher-presented question using student designed/selected procedures.*

4. *Open Inquiry—Students investigate questions that are student formulated through student designed/selected procedures.*

Likewise, Daly, Adams and Bodner have developed a similar differentiation for engineering design experiences that range from Evidence-Based Decision-Making, which is a basic level in which evidence is used to choose between design alternatives, to Directed Creative Exploration, and at the top, to design as Freedom [21]. In these and many other rubrics, open-ended inquiry and free engineering design experiences are valued the most. As we developed our curriculum, we were mindful of this valuation, and thus the curriculum initially featured as much open-ended creative exploration with LEGO and as much experiential, inquiry learning as possible. We saw great promise in having students learn through these integrated experiences.

Running headlong into the higher levels of inquiry and design goals, unfortunately, are the realities of contemporary schools: a focus on high-stakes testing and teacher accountability combined with over-crowded classrooms, limited budgets, constrained classroom space, and at times a chaotic learning environment. This conflict was difficult to mitigate, despite our best curriculum design efforts to align what we know about best practices and about the constraints of school. The three curriculum design rounds outlined below show how SLIDER migrated in its approach to integrating science and engineering because of this conflict. Additionally, as the project moved forward, the K-12 science and engineering fields evolved and began to redefine some goals and approaches to standards. These changes, combined with the realities in our schools, influenced the curriculum design and are a large part of this story.

3. Sample Curriculum Unit Summary

The overall goal of the SLIDER curriculum is to develop understanding of core ideas and science practices in physical science. Concepts like force, motion, energy, light, waves, and electricity are the focal concepts for middle school physical science. Additionally, practices like experimental design, evidence-based decision-making, argumentation, explanation, and data analysis are central concepts important to develop during middle school. To understand how we built a learning experience to target these concepts, we offer this summary of one sample unit, *The Brake Challenge*. A more fully detailed dossier of the SLIDER's brand of project-based, inquiry learning that uses LEGO NXT Mindstorms^{TM} is available in Engineering Curricula Ready To Go!, and the curriculum itself is available online at www.SLIDER.gatech.edu [22].

It is important to note that regardless of the unit, the initial SLIDER design called for students to work in groups of three, each group with its own LEGO NXT Mindstorms™ kit (consisting of roughly 430 pieces). This LEGO-centric model, similar to that described by Castledine and Chalmers, would replicate the level of interaction that students in after-school programs and robotics competitions experience [23]. This kit-to-student ratio would enable students to design robots over a period of time, store and revisit design builds over time, and ensure that students would always have access to and ownership of their design artifact.

The Brake Challenge is a 4-week unit that challenges students to learn about and improve an automatic braking system connected to a tractor-trailer truck for a (fictional) trucking company. In the challenge scenario, these trucks have been involved in a high number of accidents in which they were not able to stop before colliding with vehicles in front of them at a crowded intersection near the trucking company's distribution center. The company would like to examine whether it should invest in automatic braking and collision warning systems for its fleet. A system such as this would eliminate the reaction time of the truck driver in stopping the truck and potentially allow the stopping distance to be 40-100 feet shorter (Figure 1). The students are challenged to assist the company by:

- Investigating how the automatic braking system might reduce stopping distance.
- Investigating the factors that might improve the braking system.
- Designing a new brake that improves stopping distance to avoid potential accidents.

During the 4-week unit, students (in groups of 3-4) follow an inquiry learning sequence where they:

- Define the problem and specify the needs of the challenge.
- Identify key investigations they will need to perform.
- Iteratively design and carry out investigations to collect large amounts of data across the class.
- Iteratively analyze trends in data that reveal relationships between truck design and the science that governs its behavior

- Iteratively develop conceptual understanding of force, energy, and motion through their experience and the data they collect.
- Iteratively develop arguments for design choices and test those ideas with the LEGO truck.
- Design and defend a braking system that answers the original challenge.

4. Research Design and Setting

The SLIDER project used design-based implementation research (DBIR) methodology to help guide the development of the curriculum over time. DBIR refers to an educational research approach, in which educational interventions are developed, tested and implemented within authentic settings in order to advance and refine educational theories and to explore the contextual constraints and moderating factors that constrain or shape both how the intervention is implemented and its effectiveness as a learning tool [24]. DBIR focuses on rapidly re-developing an intervention to work in its given setting, based on a variety of sources of formative data. This is necessary because many constraints that stand in the way of achieving effective implementation are not necessarily knowable during the initial design process. These constraints include state and local standards and standardized and benchmark tests that are misaligned; teachers who are unfamiliar with inquiry teaching methods; changes in school staffing; shifts in school system initiatives and priorities; and unexpected physical constraints within classrooms. DBIR allows for research teams to examine and improve the efficacy of the intervention through shorter-term, iterative redevelopment early in, and throughout, the research project's timeline [25]. SLIDER used a collection of methods including retrospective analysis of curriculum design choices, narrative accounts of design implementations, and qualitative data collection to assess each development round and to guide the iterative redesign of the curriculum.

The successive curriculum redesigns over the first three years of the project were based on multiple sources of data and feedback: existing research on science content learning, alpha testing of the activities in the laboratory (without students), curriculum design with our teachers during professional development workshops, and pilot testing curriculum in authentic contexts (i.e., with our partner teachers implementing portions of the curriculum in their classrooms). Data sources included design reflections and documentation, classroom observations, project communications, teacher interviews, and teacher reports of curriculum enactment. Through each iteration, both the curriculum and the class environment were altered on the basis of formative assessment results, as we attempted to align the curriculum with the realities of the classroom and the learning standards teachers wanted to meet.

From the beginning, SLIDER wanted to investigate the curriculum's efficacy and implementation in a diverse range of authentic classrooms, including schools: with both low income and high income communities; in rural, suburban, and urban settings; that are overcrowded (and at times chaotic), as well as schools that are controlled and calm; where an array of teacher competencies and strengths exist; and, operating under the high-stakes expectations of state standards-based assessment. SLIDER had six participating teachers from three middle schools with these profiles:

A. A low-income rural middle school with very little student or teacher turnover; implemented SLIDER with all 8th grade students; 80% free/reduced lunch; 44% white; 48% black.
B. A suburban middle school with a rapidly changing demographic population; implemented curriculum with on-level and mainstreamed, non-gifted students; 30% student turnover rate; 65% free/reduced lunch; 26% white; 50% black; 17% Hispanic.
C. A stable and high performing affluent suburban middle school (16% free/reduced lunch, 64% white, 17% black, 8% Hispanic) that implemented curriculum with students identified as high-achievers.

Individual class enrollment across the project ranged from approximately 18 to 36 students, and class length varied from approximately 50 to 70 minutes. In most cases teachers participated in SLIDER because their school or school system administrators agreed to be part of the NSF project, not because the teachers had a pre-existing desire to implement engineering or robotics in their classrooms. Because of this, most SLIDER teachers were complete novices at LEGO robotics and some began the project with little or no knowledge about project-based or inquiry learning. For SLIDER, this was an intentional part of the project plan, as one of the philosophical underpinnings of the project is that for a curriculum to be deemed effective, it needs to be able to be effectively implemented by a wide variety of teachers, and in all types of middle schools, including those that are subjected to the constraints and challenges experienced by the schools that enroll our most vulnerable children.

In order to prepare for a round of implementation within the K-12 academic calendar, the SLIDER team, throughout the project, revised and internally tested curriculum materials in the spring and summer months. Teachers then attended an annual summer institute to review and reflect on the previous year, add to their understanding of the project's goals and pedagogical strategies, and learn about new or amended curriculum materials.

5. Results

Through three rounds of our curriculum development, which took place over nearly four years, we can detail two distinct phases in each of those three rounds: Design and Implementation. In Design, we highlight the standards and objectives for the units, the experiences we intended students to have, and some activities that exemplified our intentions. In Implementation, we share what we learned about aspects of the design that were effective, the challenges of our design intentions, and any unexpected outcome or events from each version.

5.1 Round 1

Design: Previous work through the *Learning By Design*™ (LBD) project advocated use of a *Launcher Unit* at the beginning of the school year to introduce common classroom inquiry practices, build science process skills, and establish the classroom culture for the rest of the year [26, 27]. Though the unit could take 2-3 weeks, the Launcher used inquiry to more effectively help students learn scientific practices, metrics, lab safety, and the nature of science, substituting for what is generally taught (often didactically) at the beginning of the school year in the so-called scientific method unit. LBD's Launcher Units also targeted fundamental practices that students will use all year long, like experimental design, data analysis, and sense making from evidence.

The SLIDER team wanted to develop a curriculum unit to address these concepts, as well. The project team also recognized the need to develop understanding of engineering processes, conventions, and robotics in order to have students effectively design, build and program a LEGO product that could address a challenge. In the context of the Brake Challenge described earlier, the unit would require student groups to learn experientially about:

- building LEGO structures that are strong and inflexible (i.e., the chassis for the truck),
- incorporating, spatially, the CPU and motor into the physical truck in order to design the physical emergency brake system,
- programming the CPU to actually operate the emergency brake.

To promote a high level of inquiry and engineering design, we also planned that students would be able to systematically and freely vary the design build and program to test various design options.

The first half of the unit introduced the students to the LEGO NXT, familiarized them with the different LEGO pieces, challenged them to explore build techniques, and culminated with a simple design challenge. The second half introduced the basic concept of programming as a series of sequential instructions, took students through the basics of programming the LEGO NXT central processing brick, and culminated with a simple programming challenge. The entire launcher unit was designed to span 14-16 school days, depending upon implementation pace.

Implementation Results: Curriculum developers designed and tested the launcher unit with 3 teachers and 11 classrooms of 8th grade physical science students. Teachers universally saw the appeal and educational value of the building and programming, and had reacted positively to the activities during the summer institute. They enjoyed the ability to engage students in an interesting context, and noted that their English Language Learners particularly enjoyed the activities. What made the units difficult was the amount of time dedicated to building and programming, key skills for students to master if they were to propose a robotic solution to a challenge and iterate on the design to optimize the performance of the robot. Teachers reported, emphatically, that robot building and programming are not part of the standards that are most important for their students to learn in a science class. With a limited number of school days before high stakes testing, there was simply not enough time for students to realistically develop efficient LEGO NXT build and programming skills in order to integrate an authentic engineering experience. Teachers were under tremendous pressure to "get to the content" that would be tested on benchmark and national standardized tests —i.e. the science disciplinary core ideas. It also became clear that the activities that were done in groups were the most problematic because they took substantially longer in classes of 28-35 students, a size that was not uncommon in these schools.

We did see positive effort with, and response to, the inquiry element of the units. However, when students were asked to document and make sense of experiences related to design decisions and artifact creation, they struggled to write or articulate the more abstract lessons from the experience. From multiple teacher interviews and ethnographic observations, we recognized that students needed more scaffolding in the curriculum's student edition and corresponding worksheets and journals. This suggested that the more open-ended inquiry and free design aspects of the curriculum needed modification – students simply did not know how to initiate action or respond to these *in-design moments* using the content they had learned.

Finally, teachers reported a significant amount of frustration in managing design artifacts that can also double as scientific equipment in an inquiry setting. Students struggled to organize and navigate LEGO kits with 430 individual pieces, and many were not at all adept at building with LEGO. Teachers struggled to gain proficiency in both building and programming. One teacher, even after four years of professional development and countless coaching sessions, reported this as her most challenge aspect of teaching engineering and science through SLIDER:

> *"If I had to do any of that programming, to try to, on my own, know how to make the little brain/robot part do anything, that would be a challenge for me because I don't have any experience with that."*

While this teacher may certainly have been able to develop her programming and design skills over time, the comment is indicative that some teachers were inclined to view engineering simply as an add-on, rather than an integrated piece of the science learning experience.

5.2 Round 2

Design: Based on data collected during Round 1, we redesigned the curriculum significantly, decreasing the time spent on developing build skills and eliminating LEGO programming instruction entirely. These changes and compromises had a profound effect on the curriculum as a whole; without the LEGO skills instruction, students would not have a common competence level to use the LEGO NXT as a manipulative or know how to program the device. As a result, later activities had to be more tightly scaffolded and constrained. As an example, an activity that initially required that students independently design a braking system for the LEGO NXT robotic vehicle (built by the students from build instructions) was modified so that students instead built a standard, uniform brake assembly and multiple brake shoe designs from LEGO build instructions, then redesigned and tested brake pads and shoes from a mix of materials to make the assembly more effective.

We also abandoned the Launcher unit approach to developing science practice and skills separate from disciplinary core ideas, again because of time constraints in the classroom. The unit challenges would be tied to a specific physical science disciplinary core idea, where we embedded skill introduction and development into the challenge. Thus, experimental design, argumentation, problem understanding, and solution generation were all woven into the design challenges for more seamless and expeditious coverage of learning goals. We expanded coverage of argumentation and reasoning in the curriculum specifically as a way of tying together science and engineering, because we wanted students to make design decisions based on the science they were learning. This increased the length of the units, but teachers agreed that this format was more intuitive and, from their perspective, eased pressure on their already tight schedules.

Because these experiences took place in core science classes, core science practices, not LEGO design and build skills, were the critical learning goals. The SLIDER curriculum therefore required that students design and execute their own experimental procedures, but the LEGO builds were tightly controlled. We thereby maintained the level of science inquiry at the *Guided Inquiry* level, but the engineering design was highly scaffolded, without many degrees of freedom. For instance, because the curriculum no longer required that students learn to independently program the LEGO CPU, the brake design activity could no longer be designed to allow students to test the effect of increasing the power applied to the brake or to experiment with different timing delays.

Finally, the curriculum incorporated more explicit attention to skills, practices and core ideas within the student edition and in teacher facilitation. Students previously were unable to abstract the larger ideas from only their experience and a facilitated discussion. Throughout the student materials we added text under the heading, "Reflect & Connect" to help students 1) better abstract larger meaning about core ideas and practice from their ongoing inquiry and design process, and 2) integrate aspects of engineering problem solving more frequently so that teachers would attend to that aspect of the curriculum more significantly than they did in Round 1.

Implementation Results: Curriculum developers designed and tested the new units with 5 teachers and 23 classrooms of 8th grade physical science students. During the implementation we found that our use of LBD-like guided inquiry, combined with the use of a design artifact, created an unforeseen problem. The SLIDER units intentionally created situations where students planned and carried out experiments using their interim design artifact (e.g., the LEGO truck) to collect meaningful data that revealed important relationships between science concepts. For example, students ran experiments to determine the effect of mass on the kinetic energy of a moving truck and they designed gearboxes to generate and utilize mechanical advantage to lift a heavy load with a very small amount of applied force. In both instances, because the students had not learned to effectively design and build with LEGO, the curriculum materials had to instruct them on how to build the experimental apparatus. If the build did not perform reliably, the students could then not triage the device without the teachers' assistance. Additionally, we were surprised by the lack of consistent function in the builds and sensors students used to collect data. While LEGO parts snap together easily, the resulting objects can have flex and friction that distort the data collected during an experiment, and the LEGO sensors proved to not be reliable and consistent over time [28]. In some cases, the internal friction in a well-constructed gearbox actually negated the true theoretical mechanical advantage of the gearbox, effectively disproving the force-distance tradeoff, and potentially leading students to discover misconceptions rather than real science concepts.

Once again, our pre/post assessments following Round 2 revealed that students developed greater understanding of physical science core idea and practices. Teacher interviews and ethnographic observations also made clear that students, and to some extent teachers, were marginalizing the engineering aspects of the curriculum. Students inconsistently completed engineering-focused student work and worksheets. Teachers sometimes truncated these sections of the curriculum to make-up time lost to triaging the LEGO issues. In the end, we decided that if engineering were to be a distinct learning goal, as the NGSS charge, then we would need to be more explicit about it all through the curriculum.

5.3 Round 3

Design: To increase the focus on engineering, we made some structural changes to the curriculum and increased the focus on the engineering learning goals during our summer institute with teachers. We audited the curriculum materials and more explicitly labeled and attended to the three NGSS core ideas for engineering: problem understanding via constraints and criteria; designing solutions; and optimizing the solution to best meet the problem specifications. We dedicated whole sections of the inquiry arc of units to specifically address these three concepts. This included amending the last section of The Brake Challenge, including the designing and testing of the brake shoe and pad described above.

The SLIDER version during Round 2 included the brake design activity as a three-day activity that was a continuation of the general challenge and was included with the rest of the curriculum in a single student book. To better emphasize the engineering, we removed that section from the student edition entirely and handed the students a new student text: The Engineering Notebook. Here, students revisit challenge specifications they've discussed along the way, review previous design ideas and their arguments for those designs, and plan final designs. They use specific sheets in the packet to help guide their planning, building, and testing of the group's designs. Finally, they submit in writing a letter to the trucking company detailing their design, data from its test, and science conceptual knowledge (e.g., balance of forces, friction, changes in motion) that explains its performance. The entire culminating event of the unit is almost solely an engineering design experience, intended to challenge students to craft and explain their solution to the challenge.

Implementation Results: Curriculum developers designed and tested the new units with 3 teachers and 13 classrooms of 8th grade physical science students. The dedicated engineering notebook meant our focus on engineering was now highly explicit. The clear tradeoff was that engineering was now seemingly only attended to during those sections, rather than it being a more organic, ongoing aspect of the experience where students might have led the discussion or attention in that direction.

Teachers also reported that while they valued these sections, they remained skeptical that activities that didn't directly address the science standards were worth the time they required. Regardless, observations and teacher interviews suggest that this implementation was more in line with what SLIDER intended all along. Furthermore, our preliminary assessments suggest that students did develop their understanding of the three NGSS engineering core ideas without sacrificing development of physical science core ideas and practices. In some classrooms, students were integrating the science and engineering during their final design, as this teacher interview response suggests:

> Teacher X: *When they got to work with different things like the different braking materials and that kind of thing, they pretty much understood what the truck needed to do. They pretty much understood what forces are involved, and most of them could actually show you the [force vectors for] what forces are [at work]. They used that to come up with some pretty good ideas on what materials they could use.*

In other classes the impact of our engineering activity was less robust:

> Researcher: *What about the idea of iterating on a design and testing multiple solutions in order to find one that best fits the criteria?*
>
> Teacher Y: *I think they understand the concept. I think they can be lazy. They can kind of train to do just "good enough"... I had kids who finished early, had plenty of time to do a third iteration and chose not to because it wasn't required. I don't know that they would understand that in the real world working for an engineering firm they might be expected to keep trying until they get the best product they can….Yeah, that was a little disappointing to me.*
>
> Teacher Z: *I don't know that they really have this big connect that [this] was engineering… even though we talked about it, or I tried to all year long. I'm going to be honest, I think some of [the students] feel like (pause), that when you're [focusing on engineering], you're not teaching the standards.*

As illustrated in Table 1, over the course of three rounds of development and implementation, the SLIDER curriculum evolved to more effectively integrate science and engineering in a manner that was implementable by teachers in a diverse array of classrooms.

6. Discussion

Many of the issues and challenges we describe here stem not from the inherent challenges of curriculum development, but rather from the interaction of the curriculum we developed with a complex array of school-level factors. To varying degrees across the schools we have worked with, classroom size, space, scheduling, teacher knowledge and beliefs, and high-stakes testing have impeded or thwarted our efforts to integrate engineering and achieve the possible impact we envisioned. Despite these constraints, we eventually found a balance as the curriculum evolved to integrate engineering to the deepest extent possible without compromising science learning within our highly challenging classrooms. The initial SLIDER curriculum (Round 1) represents our attempt to realize the vision of synergy between science and engineering described in the NGSS Framework. After thoughtful, methodic iteration and development of curriculum we arrived at a version (Round 3) that was implementable given all the complex educational systems issues described above. However, it is debatable whether that final version of SLIDER operationalizes the full vision of engineering put forth by the NRC.

It is questionable how realistic it is for any curriculum to fully integrate engineering into traditional, often siloed, secondary core science classes without a change in the traditional system of school. The reality is that the infusion of engineering concepts that are related to, but not completely congruent with, existing science standards by necessity takes a significant amount of instructional time if both concepts are to be mastered, a point echoed by others [15, 29]. We have seen that in high achieving and highly resourced classrooms looking to extend and enrich student learning beyond simple mastery, this type of infusion is achievable. In classrooms where teachers are confronted daily with multiple issues that impede student learning, such as regular disruptions, absenteeism, over-crowded classrooms, and low-level chaotic activity, adding engineering disciplinary concepts to the list of science learning goals is problematic at best. Even so, SLIDER's work reinforces the idea that engineering challenges seemingly remain an effective hook to drive and scaffold science learning.

7. Conclusion

The SLIDER story detailed in this paper illustrates a number of considerations and implications that may inform future efforts to meaningfully integrate engineering within the K-12 science classroom. We quickly discovered a need to be strategic about the degree to which our curriculum would foster open inquiry and independent, free design experiences. Open inquiry and free design are difficult on their own, let alone trying to facilitate them simultaneously within the complex context of public school classrooms. Ultimately, SLIDER integrates problem understanding, solution design, and optimization into a well-designed, inquiry curriculum. Our preliminary results from student assessments (multiple choice items, performance assessments, and coding of student work) demonstrate that students in all our classes develop understanding of core physical science ideas and practices. However, in order to achieve these science learning goals, students participating in the SLIDER curriculum engaged with the engineering concepts less frequently and less robustly than we had initially envisioned.

In addition to insights on the challenges of integrating science and engineering, each round of development yielded new appreciation for the opportunities and limitations of using LEGO as a manipulative for engineering within the core science classroom. The engineering design process within SLIDER requires students to create, test, and iterate on their designs using LEGO robotics materials as manipulatives. Manipulatives like LEGO have benefits, such as student familiarity with the materials, the relative durability and uniformity of LEGO blocks vs. other craft materials often used in K-12 classrooms, and the unique potential to explore physical science concepts using sensors and programming. This current work shows that finding time to develop functional knowledge with these manipulatives among both students and teachers is difficult. While we witnessed each of the aforementioned trials and challenges at all of our schools, developing fluency with LEGO was very difficult (sometimes, seemingly impossible) at our mid-to-low socioeconomic status (SES) schools (Schools A and B), which are under different pressures than School C. This, of course, should not come as a surprise, since SES levels often correlate with a wide array of education challenges.

Ultimately, we mediated these challenges by transitioning from the open, free-builds and independent programming included in the initial curriculum to a more structured, prescribed approach. Other manipulatives may exist that do not have these same limitations. For the SLIDER curriculum development team, however, finding a manipulative that is broadly accessible, is easy for middle school students to use to design artifacts, and that can produce real scientific data that reveals and develops core idea relationships and principles remains a challenge.

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Biographies

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Acknowledgements

The authors would like to thank Sabrina Grossman and Jayma Koval from CEISMC at Georgia Tech for contributing to this work. This research was funded by the National Science Foundation under DRK-12 Grant #0822241. Any opinions, findings, and conclusions or recommendations expressed in these materials are those of the author(s) and do not necessarily reflect the views of the NSF or the Georgia Institute of Technology. For additional information about SLIDER curricula and research see http://www.slider.gatech.edu/.

Figure 1. A SLIDER truck engages its auto-sensing emergency brake to avoid a collision

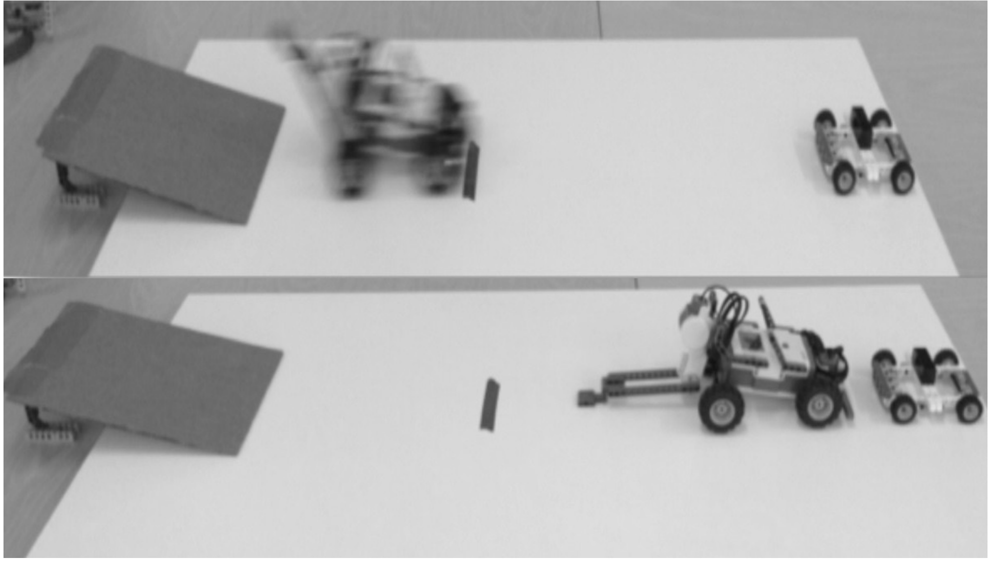

Table 1. Evolution of Engineering and Robotics within the SLIDER Curriculum

SLIDER Iteration	Implementation Findings
Round 1: Open or guided design activities using LEGO robotics kits. Frequent cycling between engineering design process and science inquiry.	Due to insufficient instructional time, students were not able to become proficient in design/programming skills required to create LEGO manipulatives that could collect reliable data for investigations.
Round 2: Engineering design activities become more structured. Students complete and modify prescribed LEGO builds and programs.	Continued issues with insufficient instructional time, material management, and generating reliable data with LEGO manipulatives. The engineering design process was marginalized relative to science content and students did not spontaneously apply science concepts (forces, friction, net force, and acceleration) to engineering challenge.
Round 3: Continuation of structured design. Engineering activities are made more explicit within the curriculum and teacher PD.	Continued concerns among teachers about devoting time to engineering. More consistent and meaningful engagement in engineering activities through culminating design challenge and Engineering Notebook. Variation in the degree to which students and teachers integrated science and engineering.