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Robotics in the Core Science Classroom: Benefits and Challenges for Curriculum Development and Implementation (RTP, Strand 4)

Dr. Marion Usselman, Georgia Institute of Technology

Marion Usselman is a Principal Research Scientist and Associate Director for Federal Outreach and Research at the Georgia Institute of Technology's Center for Education Integrating Science, Mathematics and Computing (CEISMC). She earned her Ph.D. in Biophysics from the Johns Hopkins University and has been with CEISMC since 1996 developing and managing university-K-12 educational partnership programs. She currently leads up a team of educators and educational researchers who are exploring how to integrate science, mathematics and engineering within authentic school contexts and researching the nature of the resultant student learning

Mike Ryan, Georgia Institute of Technology

Mike Ryan is research faculty at the Georgia Institute of Technology's Center for Education Integrating Science, Mathematics and Computing (CEISMC). Mike has expertise in the design and use of project-based learning (PBL) to facilitate standards-based learning.

- Mike is the Co-PI for the NSF-funded project Science Learning Integrating Design, Engineering and Robotics (SLIDER), overseeing curriculum design, teacher learning and research strategy. The project investigates the integration of engineering in science classes to facilitate physics learning.

- Mike is senior personnel for another NSF project, AMP-IT-UP, that is studying STEM integration. He designs curriculum, PD, and strategy for the project.

- Mike is active in designing and researching online learning courses in PBL for educators. Mike has also previously taught secondary science in public schools.

Mr. Jeffrey H Rosen, Georgia Institute of Technology

After 14 years in the middle and high school math and engineering classroom where Mr. Rosen was working on the integration of engineering and robotics into the teaching of the core curricula classrooms. He has now been at Georgia Tech's CEISMC for the past 8 years working on curriculum development and research on authentic STEM instruction and directing the state's FIRST LEGO League competition program. Mr. Rosen has authored or co-authored papers and book chapters that address issues of underrepresented populations participation in engineering programs and the integration of robotics and engineering into classroom instruction.

Jayma Koval, Georgia Institute of Technology

Jayma Koval is a Teacher in Residence at Georgia Tech's Center for Education Integrating Science, Mathematics and Computing (CEISMC). In this role she has developed middle school science curriculum and assessments for NSF funded projects. Previously, Jayma was a middle school science teacher for 10 years and coordinator of her school's Science Olympiad team.

Sabrina Grossman, CEISMC: Georgia Tech

I am currently a Program Director in Science Education at Georgia Tech's Center for Education Integrating Science, Mathematics, and Computing (CEISMC), which is a K-12 STEM outreach center for the university. I am working on several exciting projects including working with the STEM Incubator as Problem Based Learning Specialist and teaching an online course in Project-Based Inquiry Learning. I also work on the SLIDER team developing curriculum to teach physical science with robotics and designing teacher materials to support the implementation of that curriculum. Lastly, I work on the AMP-IT-UP project, which is a NSF Foundation Math and Science Partnership to promote workforce development and to identify and cultivate the next generation of creative STEM innovators. Through my participation in this project, I assist in writing middle school science modules and supporting teachers in their implementation.

Miss Nancy Anna Newsome, CEISMC - Georgia Tech

Anna Newsome serves as an Educational Outreach Manager at Georgia Tech for two research projects funded by the Nation Science Foundation. She received a Bachelor of Science in Public Policy from Georgia Tech in 2008. After graduation Anna spent a year working for a private sector event firm before eagerly returning to her alma mater and joining the Center for Education Integrating Science, Mathematics, and Computing in January 2010. Anna completed a Master of Science in Educational Research with a concentration in Research, Measurement, and Statistics from Georgia State University in May 2013.

Ms. Marcela Nicole Moreno, CEISMC

Marcela Moreno is an Educational Outreach Coordinator for three National Science Foundation projects, SLIDER (Science Learning Integrating Design, Engineering and Robotics), AMP-IT-UP (Advanced Manufacturing & Prototyping Integrated to Unlock Potential) and Earsketch: An Authentic, Studio-Based STEAM Approach to High School Computing Education. She is also a coordinator for GoSTEM- a collaboration between Georgia Tech and Gwinnett County Public Schools. She graduated from Georgia Institute of Technology in 2013 with a Bachelor of Science in History, Technology and Society with a minor in International Affairs. During her undergraduate career, she interned with CEISMC's summer programs division for three years before moving into her current position. She is currently working toward her Master in City and Regional Planning at Georgia Tech with a focus on environmental and health planning. She coordinates events, purchasing, and payments for her four projects.

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Abstract

The *Science Learning Integrating Design, Engineering and Robotics (SLIDER)* project at the Georgia Institute of Technology is in the 5th year of developing and implementing an inquiry and project-based learning curriculum that is aligned with the Next Generation Science Standards (NGSS) and designed to teach middle school physical science disciplinary content and practices using LEGO Mindstorms NXT as the instructional manipulative. Using Design-Based Implementation Research (DBIR) methods, the team has documented the curriculum design decisions that resulted from iterative cycles of A) design and creation of materials, B) teacher professional learning sessions, C) enactment by teachers in 8th grade classrooms, D) observation and data collection, and E) problem redefinition and curriculum redesign. These activities have taken place in a diverse set of public schools, ranging from a low-income but fairly stable rural school, to a suburban school with a rapidly changing demographic population and high student turnover, to a stable and high performing affluent school.

This paper will focus on the benefits and challenges of using robotics, in this case LEGO Mindstorms NXT kits, as a manipulative to teach science content within the core science classroom, particularly within less-than-optimal, but very common, types of school settings. It will cover the issues of materials management and constraints, resource and time requirements in different settings, the effects of variability in student prior knowledge, and the necessary scaffolding of robotic-based activities to ensure that students focus adequately on science content. Data sources include design reflections and documentation, classroom observations, project communications, teacher surveys and interviews, and teacher reports of curriculum enactment.

Introduction

Science Learning Integrating Design, Engineering and Robotics (SLIDER) is a five-year Discovery Research K-12 (DRK-12) project funded by the National Science Foundation (NSF)[1]. The project partners curriculum design specialists, educational researchers, and K-12 educators in an initiative to design and implement a problem-based learning (PBL) curriculum that integrates science and engineering to teach eighth grade physical science standards, using LEGO NXT robotics as a context or manipulative. As SLIDER is in its final year of design and implementation, we are afforded a retrospective look at the capacity of LEGO robotics to be utilized on a large scale in traditional public school classroom settings, both from an educational and organizational standpoint.

At the time of SLIDER's conception in 2009, the popularity of LEGO robotics as an educational tool had risen substantially, particularly in extracurricular activities that promote robotics learning. In Georgia alone, the state FIRST LEGO League (FLL) tournament series had grown from 48 teams in 2004 to nearly 300 teams by 2010[2]. The popularity of extracurricular robotics programs opened the door to a number of studies focused on the effectiveness of specific LEGO robotics lessons[3,4,5], after-school programs[6], and robotics summer camps[7].

Despite this surge in interest for LEGO robotics, at the onset of SLIDER there was very little research regarding the implementation of LEGO robotics in formal learning environments on a large scale. A few small-scale classroom implementation studies did, however, reinforce our decision to use LEGO robotics as a manipulative for physical science instruction. Researchers had found that LEGO robots promote the development of higher order thinking and problem-solving skills in students of all ages by engaging students in their own learning through active constructivist environments[8]. Additionally, engagement with robotics had been found to increase middle school students' understanding of physics content[9]. These small scale studies and our own extensive experience with school-based robotics programs suggested several characteristics of LEGO robotics that made it an attractive choice for SLIDER – the central processing unit, known in LEGO circles as the *brick*, offers exposure to computer programming; the suite of sensors allows for creative means of data collection that could support science instruction; students could experience hands-on building through design challenges; and above all, the platform offers a customizable manipulative for curriculum designers.

SLIDER Classroom Environment

SLIDER was conceived as a Design and Development Research project where the iterative curriculum design would take place within a diverse set of public middle schools, ranging from rural, to suburban, to urban. The three participating schools that implemented the program over a 4 to 5 year period were 1) a low-income but fairly stable rural middle school (80% free/reduced lunch, 44% white, 48% black) that implemented SLIDER with all 8th grade students, 2) a suburban middle school with a rapidly changing demographic population and high student turnover (65% free/reduced lunch, 26% white, 50% black, 17% Hispanic) that implemented with regular, non-gifted students, and 3) a stable and high performing affluent suburban middle school (16% free/reduced lunch, 64% white, 17% black, 8% Hispanic) that implemented only with gifted students. Individual class enrollment ranged from approximately 18 to 36 students, and class length varied from approximately 50 to 70 minutes. It is important to note that the administrators at the participating schools and school systems agreed to be involved in the NSF project—not the individual physical science teachers who would be implementing the SLIDER curriculum in the classroom. So unlike programs where teachers self-select into a program because of interest or proven expertise, most SLIDER teachers were complete novices at LEGO robotics, some knew little about problem-based or inquiry learning, and most were assigned to the program by their administrators. 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.

The initial SLIDER design called for students to work in groups of three, each group with its own LEGO Mindstorms NXT kit (consisting of roughly 430 pieces). This LEGO-intensive model, similar to that described by Castledine and Chalmers[10], would replicate the level of interaction that students in after-school programs and robotics competitions experience, and would enable students to design robots over a period of time, storing them between uses.

With an understanding of the climate in which SLIDER was conceived and launched, we will chronicle the evolution of our use of the LEGO NXT throughout the course of the 5-year project, both as an educational manipulative within the different iterative versions of the science curriculum modules, and as a classroom management challenge for teachers.

SLIDER Curriculum Overview

Using backwards design[11], the SLIDER curriculum development team created two units of 8th grade physical science inquiry-based instructional materials, each lasting approximately four weeks. While many projects that design and implement experimental robotics curricula take place in either informal learning environments, well-controlled lab-type schools, or elementary schools, SLIDER was designed for use in three *typical* public middle schools that are subjected to very real measures of accountability and to all the pressures of budget cuts, low income and highly transient students, and very crowded classrooms. The heavy emphasis on standardized test scores was a factor that weighed heavily, not only during the iterative curriculum design process, but also on the teachers who were asked to implement SLIDER in their 8th grade core science classrooms.

The SLIDER units are based in a town with a traffic problem. In the first unit, the *Accident Challenge*, students are presented with a traffic challenge concerning a dangerous intersection that is experiencing a spike in car accidents involving large trucks hitting cars. The students act as traffic engineers to investigate the accidents and to explain the increase in incidents and injuries over the past year. After completing a set of investigations grounded in energy concepts, the students discover that heavily loaded trucks leaving a nearby factory are the cause of severe accidents. This conclusion is the launching pad for the second unit, the *Brake Challenge*, which focuses on students designing an automatic brake for the trucks while exploring concepts of force and motion.

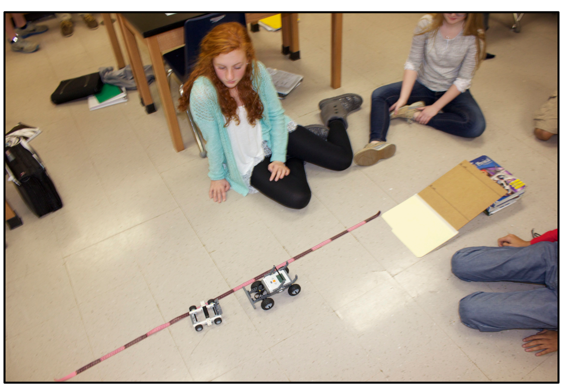
Pedagogical Approach

The SLIDER instructional materials are grounded in a project-based learning (PBL) model of instruction. In this approach, students work collaboratively in a group setting to solve problems, as well as working individually to demonstrate mastery of knowledge. They identify what they know, what they need to learn more about, plan how they learn more, conduct research, and deliberate over the findings all together in an attempt to move through the unit and solve the problem. Collaborative learning allows students to share knowledge and build off the ideas of one another. A focus on student-generated ideas is common among effective PBL curricula. The teaching strategies required of this type of instruction are very different than that of traditional text-based science, and even hands-on science[12]. Even with professional development provided by the SLIDER team, several of the SLIDER teachers were making quite a shift from their normal teaching strategies, even before LEGO was introduced.

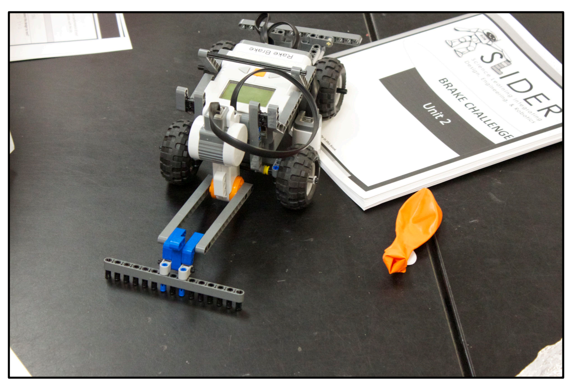
The SLIDER curriculum utilizes the pedagogical arc created as a part of another NSF-funded project, Learning by Design (LBD)[13]. LBD is an approach to middle school science education founded in constructivist learning theory that aims to address the social and cognitive aspects of learning[14]. LBD was subsequently incorporated into the Project-Based Inquiry Science (PBIS) curriculum, published by *It's About Time*[15].

SLIDER's curriculum design and instructional method is similar to the approach and protocol developed in LBD and PBIS. Like those curricula, each SLIDER unit typically revolves around a design challenge or problem that students try to solve. Students spend significant time defining the problem, thereby revealing features of the problem space or event that must be investigated to understand the overall challenge. Because SLIDER is meant as a core science curriculum, the activities and challenges ultimately must develop physical science core ideas in mechanical energy and force & motion. During the beginning of the learning arc students take notice of concrete and upfront aspects of the problem—in this case the vehicles in the scenario crash into one another because of poorly designed roadways and brakes. Students ask questions about how the *weight of the vehicles* affects the *amount of damage* during the collision. Later they wonder how the surface of the emergency braking system could *stop the vehicle* sooner during its travel.

These exercises start developing two of the abstract science concepts we want students to learn in SLIDER: that incremental changes in mass and speed will affect the kinetic energy of an object; and changing the balance of forces acting on an object will change the motion of that object. However students require additional experiences before they are ready to really understand those abstract concepts. Like LBD and PBIS, the SLIDER curriculum requires that students take their questions, identify critical factors (*variables*) and create scientific experiments that show the effect of changing those variables. Learners design and then conduct an experiment that generates multiple data points for a single condition tested. For instance students run their LEGO truck down a ramp 8-10 times, where it collides with another LEGO vehicle. Students measure the distance the struck vehicle travels after collision, as a proxy for kinetic energy transfer. They then alter the independent variable by increasing the mass of their LEGO truck, and they again measure 8-10 times the dependent variable (i.e. the distance the struck vehicle travels). This produces a large data set, where trends reveal the link between mass and kinetic energy.



Unit 1: Accident Challenge



Unit 2: Brake Challenge

This collection and analysis of quantitative data is a central design feature of SLIDER's version of inquiry learning, as it is the data that reveals the trend between two variables and ultimately provides scientific evidence of why a phenomenon is occurring. It is only after students have conducted their experiments that the curriculum links the abstract scientific concepts to the experimental data and phenomenological observations. At that point students are ready to propose solutions to the challenge that are based on both experimental evidence AND scientific reasoning. Because of the importance of quantitative data for this form of inquiry, the manipulative at the center of the experience must allow opportunities for students to collect data that reveal causal mechanisms in physics. From the beginning, we saw great potential in the LEGO NXT to deliver on this need.

It should be noted that SLIDER inquiry is a learning arc that has iterative cycles of investigation and learning within different portions of the arc. As students progress through a unit as a group, they iteratively design and improve on their design ideas, based on new data and information the group has gained. Within each unit, students design several experiments to collect data and information on multiple energy and motion variables germane to the challenge or problem. The students then use the results of these experiments to create or improve upon a solution. This process enables students to experience science explicitly and to learn the disciplinary concepts targeted in the unit. Over the course of a curriculum unit, the students engage in multiple behaviors and activities of designers, engineers, and architects.

Research Methods—Design-Based Implementation Research (DBIR)

Design-Based Implementation Research refers to an educational research approach that aims to develop, test and implement educational interventions in authentic settings in order to advance and refine educational theories and to explore the contextual constraints, moderating factors, and mediating variables that constrain or shape how the intervention is implemented and its effectiveness[16,17]. DBIR experiments may use a collection of methods including retrospective analysis of design choices, narrative accounts of design implementations, qualitative and quantitative data collection, and quasi-experimentation. In the SLIDER project, our iterative curriculum designs were tested in authentic environments, or what we refer to as *typical* classrooms, namely those challenging environments that seek to educate students from all socioeconomic backgrounds. Through each iteration, both the curriculum and the environment were changed on the basis of the formative test results as we attempted to align the curriculum with the realities of the classroom constraints. The successive curriculum redesigns were based on multiple sources of data and feedback: task analysis and 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 the curriculum in their classrooms). Data sources included design reflections and documentation, classroom observations, project communications, teacher surveys and interviews, and teacher reports of curriculum enactment.

Results

The merits of using LEGO robotics to introduce engineering design within various learning environments are widely reported. When SLIDER was conceived, several unique features of the NXT kit were thought to position LEGO to work particularly well within a project-based inquiry framework including; (1) the potential exposure to programming using the NXT brick, (2) the capacity for data logging using the suite of sensors, and (3) the incorporation of engineering design concepts as students construct structures using the LEGO building pieces. Through iterative cycles of design and implementation, with each cycle requiring designers to adapt to constraints that became evident during the previous implementation, the limits to LEGO's functionality as a learning tool have become more apparent, and the curriculum has become much more highly scaffolded. The narrative below explores this curricular evolution and the classroom constraints that drove the evolution.

Programming

The SLIDER curriculum development team initially saw the exposure students would gain to programming, by learning to program the LEGO NXT, as an immense asset. Research shows that the utilization of robotics programming can increase understanding of physics-related science content, such as *force* and *motion*[18]. The LEGO platform, in particular, makes programming obtainable for a novice by utilizing a visual "click-and-drag" system. Rather than requiring a user to learn a coding language, the LEGO platform allows students to create a visual string of actions for the robot to perform using a computer interface. The programs are then loaded from the computer onto the robot's brick.

The first iteration of the SLIDER curriculum included a series of scaffolded activities to teach LEGO programming to all students in the class. These activities worked well with the internal curriculum development team and also when piloted with teachers during the summer professional development institute. However as the curriculum was implemented in classrooms during the school year, it quickly became apparent that there was simply not enough time in a typical science classroom to accommodate the learning curve of not only the students, but the teachers as well. To be effective, the programming unit needed to start by addressing basic concepts such as how to write a logical series of instructions. It ended up requiring at least two weeks of class time, and covered none of the mandated physical science standards. And the teachers weren't themselves comfortable with programming. Even after four years in the project and numerous professional development workshops, when asked during an interview about the most challenging aspects of implementing the SLIDER curriculum, one of the teachers responded,

> "*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*."

Because of these time constraints, in the second iteration of the curriculum students were asked to download and modify prewritten programs. However even this seemingly "simple" task introduced too much complexity in overcrowded classrooms, and teachers often adapted by implementing time consuming procedures such as requiring that student groups bring their robots to the teacher one at a time for supervised downloading. For harried teachers who weren't adept with programming themselves, even this supervised procedure introduced problems that resulted in urgent phone calls to the SLIDER program staff. Therefore in the final version of the curriculum, programming was scaled back to a level in which neither the students nor the teacher interact with the LEGO program at all. Project team members preload the bricks with the necessary programs before teachers receive their materials at the beginning of the semester and students are simply asked to run specific programs. The LEGO brick essentially evolved from being a *programmable* device, to being a *smart* device that could accomplish tasks that a simple, non-robotic, manipulative couldn't. This smart device capability enabled the curriculum designers to enhance the science inquiry experienced by the students, but students no longer learned any computer programming. Since computer programming is not a learning goal in a physical science class, this was deemed a reasonable trade-off, mirroring the decisions made by some other designers of LEGO science curricula[19,20,21]. This evolution is summarized in Table 1.

Table 1: Evolution of Programming within SLIDER Curriculum						
Initial Conception	**First Curriculum Version**	**Constraints**	**Middle Iteration**	**Constraints**	**Final Curriculum Version**	**Final Conception**
LEGO Robot as a programmable device	Students program their own robots using LEGO software	Not enough instructional time to teach programming	Students download and modify prewritten programs	Teacher unease, took up too much class time	Bricks are preloaded with programs. Students hit "run"	LEGO Robot as a smart device

<u>Sensors and Data Logging</u>

The project team, from the very onset of the proposal, saw great promise in using the LEGO NXT kit as the central manipulative for a variety of reasons. The LEGO Mindstorms kit pairs sensors and a CPU brick that appeared, in the eyes of the design team, to be well suited to foster students learning physical science. These kits would allow students to program their robotic devices to engage in *if-then decisions* where the sensors read the surrounding environment. When a sensor detected changes in conditions or the environment, the NXT's program could then direct the robotic device to change its behavior or record useful data.

As an example, biologists often use motion sensors to trigger a computer to record the number of nocturnal animals that travel a known path during the night as they seek prey or water. The curriculum developers imagined a unit where students are challenged to use the same technology to record foot traffic at a dark, accident-prone intersection at night in an attempt to improve safety for pedestrians. Students could program their robotic device to count the number of pedestrians in a given time using potentially the ***sound, ultrasonic*** or ***light sensors*** in the LEGO NXT kit. Using a model of the intersection in the classroom, students would test and iteratively improve their robot to accurately record data and eventually help them make decisions about making the intersection safer. During this unit, through a number of experiments, students would explore the specifications and capabilities of each these sensors. The physical science concepts and sub-concepts associated with waves, light, and sound (i.e., *NGSS Disciplinary Core Ideas*) would become more explicit and understood during this exploration. And because the NXT allowed students to log their data into the brick, download it into Excel and display it on their laptops, the SLIDER design team anticipated that the LEGO system would enable students to better engage in science practices such as data analysis and data representation.

Several sensors were provided as a part of the kit, and there were also a few aftermarket sensors that integrated with the NXT kit materials. The designers envisioned creating curriculum materials where each of these sensors could be used to enhance the learning of several concepts:

Table 2: LEGO NXT sensors and possible associated physical science concepts	
LEGO Robotics Sensor Type	**Physical Science Concepts**
Light	Light, Waves
Color	Light, Waves
Sound	Sound, Waves
Touch	Force
Ultrasonic	Motion, Waves
Temperature	Heat, Energy Transfer
NXT Accessory with Vernier Force Probe	Force, Motion

During SLIDER's first year of development, the design team set out to test the presumed capacity of the sensors by designing and implementing several short (approximately three-day) instructional units. The purpose of these instructional units was to familiarize the teachers with the LEGO Mindstorms kit and data-logging capability, while testing the functionality of some of the sensors. Unfortunately, the sensors tended to have serious limitations as data collection instruments in the middle school classroom. From a physical standpoint, the sensors were finicky, requiring teachers to do a tremendous amount of student monitoring and handholding to make sure the students were using the devices properly. For instance, if the ultrasonic sensor was not held exactly right, the experiment would not yield reliable, usable data. The sensors were also not consistent from sensor to sensor, so different student groups came up with different results, nor were they reliably consistent over time, so readings at different times might produce different results. Aside from the accuracy and reliability problems, there were also challenges associated with the data-logging interface.

The data collected by the sensors is recorded on the CPU brick, and must be downloaded to a computer before the class can make meaning from the data. This cumbersome process became overwhelming for teachers with class sizes that often exceeded 30 or even 35 students. In addition, once the data was retrieved from the brick, the output was often not at the level of the learner. The graphs generated using the compatible software were difficult to read, forcing the teachers to regenerate their own visuals before any connection could be made between the activity and the data. This added step, necessary to actually make the data intelligible to the students, not only took up class time, but ultimately took the activity out of the hands of the students, thereby decreasing the activity's value towards promoting inquiry.

Given all these constraints and limitations, the team explored using the LEGO sensors in a more traditionally LEGO-prescribed manner in which the devices were utilized solely to enhance the functioning of a robot, not as a data-logging tool. Several sensor-centric units were developed for the classrooms, from a solar car unit that used the energy kit, to a robot jousting unit that used the light sensor. While successful in terms of implementation and engaging for the students, these activities were more didactic in nature, migrating away from the central tenet of PBL and inquiry--that students should engage in the discovery of science. Instead the activities served as a somewhat time consuming hook, but the science was then told, not discovered. Both teachers and students enjoyed the activities, but they were best reserved for the time after the standardized tests were administered in the spring, when the major goal was student engagement, not science learning.

In the final version of the SLIDER curriculum, the light sensor is utilized in the Brake Challenge, enabling students to model their engineering solution with a dynamic manipulative. The light sensor, incorporated into a robotic truck, instructs a brake to engage when the truck crosses a black line. The truck and light sensor-triggered brake assembly were designed completely by the curriculum team, not the students, as it is critical that the manipulative used in a curriculum unit produce data that is predictable to the teacher, and reproducible by the students. In the end, the idea that the sensors could be used as a means to collect reliable scientific data had been abandoned entirely. The limitations of the sensors and data-logging interface reminded everyone that LEGO are toys, not scientific tools, and that curriculum developers and teachers trying to incorporate LEGO into instruction need to be mindful of that. However the addition of a light sensor did enable the truck to become a dynamic manipulative, effectively enabling a more engaging level of inquiry than a non-dynamic or not-smart truck would have allowed. The evolution of the use of sensors and data-logging is summarized in Table 3.

Table 3: Evolution of Data-logging within SLIDER Curriculum

Initial Conception	First Curriculum Version	Constraints	Middle Iteration	Constraints	Final Curriculum Version	Final Conception
LEGO Robot as a data-logging device	Sensors would be incorporated to enable students to log and analyze data.	Sensors not accurate or reliable, and are hard for students to use effectively	Use sensors within builds suggested by LEGO Education	Activities don't support discovery of science, or scientific inquiry	Sensor is incorporated into prescribed build, to create a dynamic manipulative that promotes inquiry	LEGO Robot as a dynamic manipulative

Mechanical Design and Build with LEGO

One of the greatest perceived assets of LEGO at the onset of SLIDER was that the materials afforded the opportunity for students to actually engage in engineering design, and to build prototypes within a physical science context. In the early versions of the SLIDER curriculum, students in groups of three took part in a guided build activity in which they were introduced to the basic engineering concepts needed to construct a solid structure. Through a series of activities the students assembled a rigid structure, constructed a chassis, then finally they designed and built their own truck for the *Accident Challenge* from pieces in their assigned LEGO NXT kit. This series of activities was meant to familiarize the students with the LEGO kits, while teaching them how to build mechanically sound structures using specific LEGO parts so that they would be able to complete design challenges later in the curriculum.

Much like with the NXT programming, allowing students the necessary time to tinker and familiarize themselves with designing and building with LEGO took up entirely too much classroom time. The teachers saw little connection to the science standards they were charged with teaching, and they provided strong feedback that the instructional goals for the classroom were not being met. In addition, students all building a different LEGO device with which to collect data or conduct a scientific experiment was incompatible with the explicit SLIDER goal of creating a curriculum within which students collect common and reproducible data that enables them to discover a scientific principle through scientific inquiry. So allowing students to design their own robot, while perhaps promoting creativity, doesn't result in the students having a useful and predictable manipulative for instructional purposes.

The next iteration of the curriculum introduced a prescribed build for the LEGO robotic truck used as the central manipulative and included opportunities for the students to use additional LEGO pieces to redesign parts of the truck. Students were then instructed to collect and analyze data and were led through scaffolded activities that would allow them to generalize trends and discover scientific concepts. The design team also created activities that demonstrated the concepts of simple machines and mechanical advantage by having the students build a standard gearbox and then redesign it to change the gear ratio. Unfortunately these redesign activities still took up too much instructional time when compared to the value of the science covered—the "bang for the buck", to quote a teacher—and 30 students all attempting to take apart and redesign LEGO gearboxes, with their many gears, axels, beams and tiny bushings, created a classroom management nightmare in all but the most controlled classes. In addition, the amount of internal friction created by the LEGO pieces in the gearboxes resulted in experiments that didn't produce the expected quantitative changes in the demonstrated mechanical advantage. Inquiry learning doesn't work if the experiments that the students engage in don't actually demonstrate the expected trends.

The final SLIDER curriculum eliminated the gearbox activities, and uses a prescribed build for the robotic truck and brake. Students attach non-LEGO materials such as rubber, plastic, carpet, etc. to the brake shoe and run controlled tests to explore the effects of different materials on the stopping capability of the brake and truck and to develop their understanding of forces and motion. They then engage in the engineering design process to create a new brake shoe design that stops the truck most effectively while staying within cost and material constraints. Using non-LEGO materials for the redesign greatly simplifies the classroom management challenges and expands the ability of the manipulative to support scientific inquiry. So in the end, the only free design activities that take place in the SLIDER curriculum are done with outside products being affixed to LEGO, not designing with the LEGO itself. The SLIDER team concluded that promoting free design of the LEGO manipulative in a standards-driven classroom is done at the expense of the scientific inquiry, as students do not produce a working apparatus that can collect reliable data or that enables them to discover accurate physical science concepts. The evolution of the design and build strand of the SLIDER curriculum is summarized in Table 4.

Table 4: Evolution of Design and Building within SLIDER Curriculum

Initial Conception	First Curriculum Version	Constraints	Middle Iteration	Constraints	Final Curriculum Version	Final Conception
LEGO Robot as a device that promotes free design	Students would design and build LEGO structures using engineering concepts.	Not enough instructional time, students don't create manipulatives that can be used to collect common and reproducible data.	Students redesign prescribed LEGO structures and collect data.	Not enough time, introduces materials management issues, and students can't collect useful data.	Prescribed builds with engineering design activities that use non-LEGO components	LEGO Robot as a device that provides build experience, and a platform for design with other materials

LEGO Materials Management

Issues of materials and classroom management were at the forefront of the project team's concerns, not only before the program was launched, but also as an ongoing concern during the three-year development cycle of the curriculum. The initial implementation plan featured one LEGO NXT kit for every three students, with teachers each teaching four classes of 8th grade physical science, enrolling no more than 30 students in each class. In the real world, some teachers taught five physical science classes, and after the economic upheavals in 2008 and 2009, some classes had more than 35 students enrolled. So in some cases teachers had to manage over 50 NXT kits, each with 431 pieces, in one already crowded classroom. Aside from the obvious logistical challenges that arose from putting hundreds of tiny pieces into the hands of dozens of students at once, the SLIDER team had to create a secure storage plan so that students' robots wouldn't be handled by students in other class periods and so 50 robots could be charged up at once. The initial plan entailed retrofitting one large, lockable, metal storage cabinet per class period with power strips. This layout could house 10 NXT kit boxes and 10 constructed robots, enabling student teams to retrieve their charged robot and kit of remaining parts at the beginning of the period. However fitting five large cabinets just for materials storage into a typical classroom, while situating them near power outlets, generally turned out to be impossible, so teachers jerry-rigged storage solutions depending upon their local constraints.

As curriculum development commenced, the SLIDER team had to find a balance between time spent for students to grapple with and learn science content, versus time spent for students and teachers to identify, select, and sort LEGO pieces, and for them to repair the inevitably broken robotic trucks. Experience with well-run extracurricular robotics clubs suggested that students could be trained to take ownership for their NXT kit, making sure that the high value components (bricks, motors, sensors) were all accounted for and keeping the pieces at least marginally sorted. That proved to be impossible in most of our classrooms, and NXT kits were returned to the SLIDER team in the spring in complete disarray. And as might be expected, kits were also sometimes accidently dropped during class, causing enormous teacher angst and completely jumbling the kits. Hiring student assistants to completely re-sort 250 NXT kits was an unexpected expense for the project, and introduced a serious curriculum sustainability issue.

To reduce the number of physical LEGO kits the teachers had to contend with, the project team moved away from the "one kit per student group" model, opting for a new *buffet* style system instead. The teachers, project manager, and curriculum designers worked together to develop the buffet style system for organizing and managing the LEGO kits in which the kits were disassembled and reorganized in the NXT boxes by part. For example, all the beams from an entire class set of NXT kits were placed in one bin, sorted by length into the original kit's plastic sorting trays. The same system was replicated for bins of axles, wheels and tires, pegs, and so on, with parts that weren't used (like the red and blue balls and LEGO people) removed entirely. Each *class set* then consisted of eight bins, each organized by part, rather than ten to fourteen individual kits. Students were only given responsibility for their robot, not for a kit full of extra pieces.

On class build days the teacher would set out bins at the start of each class period, giving the students access to only the parts they needed that day. The design team gave teachers a set of *build cards* that indicated which parts the students needed that day, and covered the parts of the sorting tray within each bin that housed parts that were not needed for that particular build. The bins were organized in a "buffet line" in which students filed through with cardboard sorting trays, collecting the needed parts from each bin. From a management standpoint, while easier to handle than giving each student group a kit, the buffet system still presented challenges in set-up and storage for the teachers. Furthermore, as the students were LEGO novices, having access to too many parts, even with explicit instructions, hampered their ability to accurately follow the build instructions. They often would take the wrong size pieces from the buffet, particularly with beams and axels. These errors wouldn't become apparent until later when the build would not come together correctly—a problem that quickly ate into instructional class time.

The final iteration of the SLIDER curriculum completely eliminates the need for students to identify and retrieve LEGO parts. Abandoning the buffet line entirely, streamlined SLIDER kits were built out by project staff members, using only the LEGO parts that are needed for the truck and brake builds. These specialized kits were housed in large zip-top plastic bags and delivered to teachers in large plastic storage bins that took up only a fraction of the space required by full kits. While students still build their own trucks, the specific designs are entirely predetermined by the curriculum developers, and students are only given access to the parts that they need. Table 5 summarizes the evolution of the SLIDER LEGO management system.

Table 5: Evolution of Materials Management within SLIDER Curriculum

Initial Conception	First Curriculum Version	Constraints	Middle Iteration	Constraints	Final Curriculum Version	Final Conception
Students have open access to LEGO pieces	Each student group of 3 students has an NXT kit assigned to it.	Kits become jumbled, students have access to too many pieces, takes up too much room in classroom.	LEGO pieces sorted into bins, and students retrieve needed pieces from a buffet line.	Students aren't reliable in picking out correct pieces, resulting in faulty builds. Requires teacher time to set up.	One kit per student group in zip-lock bag that only contains pieces needed for the build.	Students have defined kit of LEGO pieces

Conclusion

Five years of iteratively designing and testing 8th grade physical science curriculum activities using LEGO Mindstorms NXT kits as a means of integrating science and engineering have revealed the strengths and limitations of trying to use LEGO robotics to teach standards-based inquiry science. These lessons are both pedagogical and practical.

First, though the LEGO manipulative itself can serve as a vehicle for creative design when utilized within engineering or extracurricular settings, letting students freely design their science data collection instrument is incompatible with students collecting the types of reliable and reproducible data that is necessary if they are going to be able to extract meaning from scientific experimentation at the middle school level. On the other hand, the LEGO NXT does enable curriculum designers to devise a smart or dynamic manipulative that can support science inquiry in creative and engaging ways. As one of the SLIDER teachers noted, studying friction by trying to design an effective brake shoe for a robotic truck is much more engaging than the traditional experiment of dragging a block of wood across a desk. However the students themselves can't easily design the manipulative if it is going to support scientific inquiry.

Second, the middle school physical science curriculum is generally tightly packed with required science content, leaving little time for students to really engage in important science practices, let alone learn valuable but tangential content like computer programming or the basics of mechanical engineering construction. These latter skills are appropriate for engineering or computer programming classes, and are valuable for students to tinker with within FIRST LEGO League teams. However within the SLIDER core science classrooms, where most students had no prior experience with LEGO robotics, we found that these engineering and computer science skills became added learning goals that didn't align with the physical science standards, and couldn't be accommodated within the allotted class time without jeopardizing student learning of required science standards. If students entered the physical science class with the requisite LEGO programming and building skills, the manipulative might have been able to support a different type of instruction. However that wasn't the case in our schools.

The final lesson learned is that trying to use a manipulative that introduces enormous materials management challenges into what is already an often chaotic and stressful environment doesn't work well. Giving students free access to lots of little LEGO pieces might theoretically promote engagement and responsibility, but in our experience it instead primarily adds confusion and detracts from learning. In SLIDER we provide very defined LEGO kits where students use all the pieces in the prescribed build. Anecdotally, teachers have reported that building the robotic truck seems to increase the students' ownership of the manipulative and serves as a hook for some children. On the other hand, the teachers also note that some 8th graders are inclined to dismiss LEGO as a toy worthy of distain. Overall, whether the actual physical building with the LEGO increases engagement remains to be determined. Because there is no free design with LEGO, the heart of the final SLIDER curriculum can be implemented by teachers who have only one class set of LEGO kits (i.e. one kit for every three students in the largest class), and the trucks can be reused by each sequential class. Scaling back the use of the LEGO pieces, through eliminating the LEGO building experience and using the same set of trucks all day, may ironically enable more classes to experience the inquiry science made possible by the use of the LEGO robots.

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