AC 2011-908: STEM INTEGRATION IN A PRE-COLLEGE COURSE IN DIGITAL ELECTRONICS: ANALYSIS OF THE ENACTED CURRICULUM

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STEM Integration in a Pre-College Course in Digital Electronics: Analysis of the Enacted Curriculum

Abstract

There is agreement amongst educators, policy makers and professionals that teaching and learning in STEM areas at the K-12 level must be improved. Concerns about the preparedness of high school students to improve the innovation capacity of the United States are leveled following data showing US students performing below students in other industrialized nations on international math and science tests[1]. To address both the preparedness for and the appeal of engineering, technical education programs have emerged that provide hands-on, project-based curricula that focus on the integration of mathematics and science knowledge with engineering activities. Learning Sciences research emphasizes that integration of new ideas with prior knowledge must be made explicit to learners in order to promote successful transfer to novel problem-solving and design contexts[2]. Thus, integration of mathematics and engineering is important both for mainline (general education) as well as pipeline (career preparation) goals for engineering education[3].

Increasingly, research on high school engineering curricula is focused on the nature of classroom instruction and its impact on student learning. The current study uses actual classroom observations to try to understand how students in the high school classroom learn and integrate mathematics and engineering skills and concepts based on the teacher's actions in a portion of the *Project Lead the Way* (PLTW) *Digital Electronics* ™ curriculum. *Digital Electronics* ™ is a unique course in that it utilizes mathematics concepts such as Boolean algebra that are beyond the scope of most high school mathematics standards. Thus, while students are likely to have little direct prior knowledge, there is a greater need for explicit introduction and integration of the math that is used in this curriculum than is typical for K-12 engineering curricula overall[4,5,6].

To summarize our major findings: The PLTW *Digital Electronics* ™ (DE) curriculum introduces a great deal of mathematics to students that goes above and beyond the national high school mathematics standards. The mathematics taught in DE is equally skills and conceptually based. Students learn about numbers, Boolean algebra (its notation, transformation and various important theorems), truth tables and Karnaugh maps. These learning opportunities are primarily through project work and tutorials, which constitute 74% of the instruction time in our sample. Process standards of mathematics such as problem solving, reasoning and making connections are also used to complete projects. The engineering skills and concepts used in this curriculum are focused on wiring circuits, and solving (Boolean) logic problems related to circuit design. Explicit connections between mathematics and engineering were observed 78% of the time. This is primarily because the mathematics and engineering in digital electronics work is practically inseparable. That is, in order to achieve the project goals, students must be taught mathematics skills and concepts, which then form the basis for the primary engineering skills and concepts of the lessons.

Introduction

Motivations for the Study: The Importance of Explicit Integration for Knowledge Transfer

There is a growing emphasis on getting students interested in engineering and engineering careers early on. This emphasis is in response to the concerns voiced by various groups about the diminishing status of the United States relative to other countries[7] with regards to the engineering pipeline. As students engage with curricula such as *Project Lead the Way*™ (PLTW), we look to understand how these programs help students increase their capacities in both academic subjects and career preparedness. These dual goals can be achieved partly through explicit integration of mathematics with the engineering material. Learning Sciences has taught us that such explicit integration promotes transfer of knowledge from the classroom to novel contexts[8,9,10].

The Enacted Curriculum

The *enacted curriculum* refers to the specific content as it is taught by teachers and studied by students during the course of learning and instruction. Work on assessing the enacted curriculum was done to create a dependent variable for use in research on teachers' content decisions[11]. In contrast to the *intended curriculum*, which depicts the idealized classroom experience, as stated in the printed teacher and student textbooks, the enacted curriculum is empirically established. Observations show that the enacted curriculum is dynamic – it often deviates from the intended plan and varies from teacher to teacher and classroom to classroom based not only on the teacher's actions, but also on the student needs. Students generally learn what is presented in the classroom and may miss elements that were intended to be incorporated by the textbook or curriculum authors[12]. Further, content of the enacted curriculum is a reliable predictor of student achievement gains[13, 14]. Measures of the enacted curriculum can also be used to investigate the quality of instruction and curriculum implementation[15]. Consequently, analysis of the enacted curriculum is an important piece of curriculum research overall. In our case we study the enacted curriculum to try to understand where explicit integration occurs, which in turn addresses some of the necessary pre-conditions that allow students to transfer knowledge to new tasks and new situations beyond the specific classroom experiences.

In earlier studies, we analyzed the enacted curriculum of the first two PLTW foundations courses, *Introduction to Engineering Design*™ and *Principles of Engineering* ™. We found that a trend toward the use of the instructor's time for tutoring and working with students occurs as one moves through the sequence. Whereas in the first course, more of the instructor's time was spent on class management (i.e., non-instructional tasks)—especially collecting and grading team project work—once students get to later courses in the PLTW program sequence, they spend more time working on projects with one another and with the help of the teacher. Secondly, as students move through the foundations courses, focus shifts so that students learn not only the skills but also the concepts and contextual basis for their learning. Lastly, while in the *Introduction to*

Engineering™ course, only a small fraction of instruction linked mathematics with the engineering content, in the *Principles of Engineering*™ and especially in the *Digital Electronics*™ classrooms, these links are more frequent and made more explicit[16]

Research Questions

PLTW offers a four-year, pre-engineering curriculum, *Pathway to Engineering*™, which has been adopted by over 10% of all US high schools in all 50 states. All PLTW courses are project based, allowing for unique opportunities to view how teachers and students interact to bring the curriculum alive. In previous studies, we analyzed the curriculum of the first two foundations courses of the PLTW sequence – *Introduction to Engineering Design* ™ [17]and *Principles of Engineering* ™ [18]as well as the intended curriculum of all three courses[19]. These first two courses introduce students to engineering and what engineers do and allow students to explore the kinds of projects (primarily mechanical) engineers work on. *Digital Electronics* ™ is the third and most advanced foundations course in the sequence. It includes lessons in applied logic and extends students' work into digital and analog circuit design and testing. Importantly, it incorporates mathematics that is beyond the scope of the high school curriculum and beyond the mathematics standards recommended by the National Council of Teachers of Mathematics (NCTM) for grades 9-12[20]

Analysis of the enacted curriculum has allowed us to focus on how teacher/student interaction occurs, how students work with technology and to gain insight on how project work is done in the classroom setting. In applied work, such as was observed for this research, a study of what the students are doing in the classroom is especially rich. Students used a variety of skills and concepts in a number of settings, including programming robots, designing circuits in the Multisims simulation environment, and breadboarding to create and troubleshoot circuits. In these contexts, one can observe how students are taught lessons that involve mathematics and subsequently use those to complete their projects.

The analyses were motivated by three research questions:

1. How is class time distributed between teacher-centered instruction, teacher-directed tutoring, student-directed collaboration, and non-instructional tasks? Further, since this is a project-focused curriculum, how do students work in-class to complete these projects?
2. What portion of class time is spent on concepts and skills that are central to STEM education (both mathematics and engineering)?
3. How frequently do we observe *explicit* integration of mathematics ideas in engineering activities and lessons?

Data and Methodology

This paper reports on preliminary findings from our mixed methods analysis of video data from seven PLTW lessons from the foundations course *Digital Electronics* ™ as implemented in an urban high school. The lessons observed covered two project areas: programming a basic stamp robot (3 hours) and the creation and troubleshooting of circuits using the computer program Multisims and breadboards (4 hours).

First, the videotapes were digitized and entered into Transana[21](see www.transana.org), a computer application for discourse analysis that integrates the video, transcript text and codes. Classroom sessions were segmented into clips, and clips were coded to reflect the points of interest noted in our research questions, in a manner similar to Nathan et al., 2009[22].

Coding Framework

Our coding framework delineates four different dimensions:

A. *Instruction time* codes subdivide each class period based on how the instructor interacts with students.

B. *Project work time* provides data on how often students are working individually, with the instructor, within groups or alone in order to complete assignments within the PLTW curriculum.

C. *Concepts* mark engagement with "big ideas" from STEM, such as modularity in engineering and projection in mathematics. We separately note whether the math concepts are explicitly integrated during instruction.

D. *Skills* address process-oriented tasks that may not require conceptual understanding but are important for doing practical engineering work.

Instructor's time

The instruction time code group allows us to characterize how the instructor allocates class time during lessons. This code is directly relevant to our first research question and stands to shed light on how a typical day of PLTW instruction in each DE classroom is broken down. The codes and descriptions for this data dimension are given in Table 1.

Table 1: Instructional Time Codes

Code	Description
Lecture	Teacher is engaged in large-group instruction, including lecture-style teaching and demos directed at all or nearly all of the students in the class.
Tutorial	Teacher is engaged in one-on-one or small group tutorials, including teaching or reviewing of concepts as well as hands-on how-to's and troubleshooting.
Worksheets	In *Digital Electronics*™, mathematics worksheets are included in lessons due to the need to introduce ideas like Boolean algebra and logic.
Class management	Teacher is engaged in administrative, disciplinary, or other non-instructional tasks, including collecting homework, etc.
Non-instructional interactions	Teacher is interacting with the students, but instruction is not happening.
Non-interaction	Teacher is not interacting with students and may be grading, doing preparation, conferring with colleagues, etc.

Project Work

Project work codes were developed to help give us more insight as to how students completed the hands-on portions of the DE curriculum. Since much of the project work done in this curriculum relies on resources available only in class, we felt that it was important to review how time devoted to project work was spent with the student as the reference point.

Table 2: Project Work Codes

Code	Description
Student works alone	The student is completing an aspect of the project work on his/her own.
Student/ Instructor	The student interacts directly with the instructor, who answers questions, provides feedback on written components, checks hands-on work, questions the student, etc.
Student/ Student	The student interacts directly with one or more other student in order to complete the project. The students may engage in tutoring one another, bouncing ideas off one another, or collaborating to problem solve.

Concepts

Concept codes identify segments of class time that revolve around the central organizing ideas from mathematics and engineering. The individual codes in this group, shown in Table 3, were taken from mathematics standards recommended by the National Council Teachers of Mathematics (NCTM) for grades 9-12 as well as elements of the engineering design process. Additionally, in some cases we included codes that reflect important concepts identified in various scholarly[23], regulatory/professional[24,25], and popular[26] accounts of the study and practice of engineering. Lastly, some of the codes were derived from classroom observation itself.

Table 3: Concept Codes

Code	Description
Mathematics: Algebra	Understand patterns, relations, and functions; Represent and analyze mathematical situations and structures using algebraic symbols
Mathematics: Geometry	Analyze characteristics and properties of two- and three-dimensional geometric shapes and development of mathematical arguments about geometric relationships; Specify locations and descriptions of spatial relationships using coordinate geometry and other representational systems; Apply transformations and use symmetry to analyze mathematical situations
Mathematics: Measurement	Map out the measurable attributes of objects and the units, systems, and processes of measurement and application of appropriate techniques, tools, and formulas to determine measurements
Mathematics: Number	Understand numbers, ways of representing numbers, relationships among numbers, and number systems; Understand meanings of operations and how they relate to one another; Computations performed fluently and reasonable estimates made
Mathematics: Logic	This is beyond the scope of the NCTM standards for high school math, and includes the use of Boolean algebra and Karnaugh mapping for the design of circuits and creation of robotic commands.
Engineering: Design Basis	Emphasis on the importance of creating a pre-specified "statement of the problem" or system requirements.
Engineering: Computer Simulation	Design or simulation of circuits and other digital commands using computer programming.
Engineering: Debugging Circuits	Troubleshooting circuits by following logic commands; reviewing wiring and design of circuits.
Engineering: Modeling	A representation of a design or system. Can be "literal" (as in a physical or electronic one-, two-, or three-dimensional model of the design itself) or symbolic (as in when equations, graphs, or schematics represent interesting aspect of the design). Sometimes the model is explicitly coupled to an analysis or testing/evaluation task.
Engineering: Re-Engineering	Improvement upon an existing design. This may require "reverse-engineering" if design artifacts like drawings and models are not available.
Engineering: Structural Analysis	Determine the strength of materials in a structure based on empirical testing or calculation of forces/stresses and understand the conditions necessary to conduct this analysis.

Skills

Skills codes are distinct from concept codes in that they focus on process-based procedures which allow the student to perform actions or apply learned concepts. Skills are important for competency in completing engineering projects and tasks[27] Sometimes, a student must understand an underlying concept in order to be proficient in a certain skill – for instance, in order to skillfully wire a breadboard a student may need to understand how logic gates are arranged in various integrated circuits. Some math skills are captured in the NCTM's *process* standards[28].

Table 4: Skill Codes

Code	Description
Mathematics: Communication	Organize and consolidate mathematical thinking through coherent and clear communication to peers, teachers, and others; Analyze and evaluate the mathematical thinking and strategies of others; Use the language of mathematics to express mathematical ideas precisely.
Mathematics: Connections	Recognize and use connections among mathematical ideas; Understand how mathematical ideas build on one another to produce a coherent whole; Recognize and apply mathematics in contexts outside of mathematics.
Mathematics: Problem Solving	Solve problems that arise in mathematics and in other contexts, using appropriate strategies.
Mathematics: Reasoning	Develop, select and evaluate mathematical arguments and proofs.
Mathematics: Representation	Create and use representations to organize, record, and communicate mathematical ideas; Use representations to model and interpret physical, social, and mathematical phenomena.
Engineering: Understanding Constraints	Ability to keep in mind parameters of the project while creating a solution.
Engineering: Creating Hypotheses	Generate an idea for testing based on knowledge of what might work (from math or physics, for example, or even other things that exist - a bridge in your neighborhood, something found in nature or even experience).
Engineering: Project Management	Figure out what must be done at certain time points in order to meet a deadline.
Engineering: Use of Software for Design	Use of computer aided tools for creating and modeling the project.

Explicit Integration of Concepts and Skills

We applied an additional code to any video clip coded for math skills or concepts indicating whether that skill or concept was explicitly integrated or implicitly imbedded into the surrounding engineering or technology lesson. *Explicit integration* is defined as any instance wherein the instruction specifically points to a mathematics principle, law, or formula, and depicts how it is used to carry out or understand an engineering concept, task or skill[29]. A lack of integration between one's conceptual basis of prior knowledge and new curriculum materials is problematic given research that emphasizes the importance of explicit integration for successful transfer of knowledge to novel applications or new situations[30,31]. *Implicitly embedded* concepts and skills are those in which the conceptual basis for understanding how mathematics is used for engineering is ingrained into the tools, representations or procedures used in the lesson, but not specifically pointed out by the instructor, curriculum materials or other students. Occasionally, but rarely, students will discover these connections on their own, even though they may be readily apparent to teachers, curriculum designers, and other content experts. Lastly, if there were no connections (either implicit or explicit) made between mathematics and engineering, these instances were labeled as such.

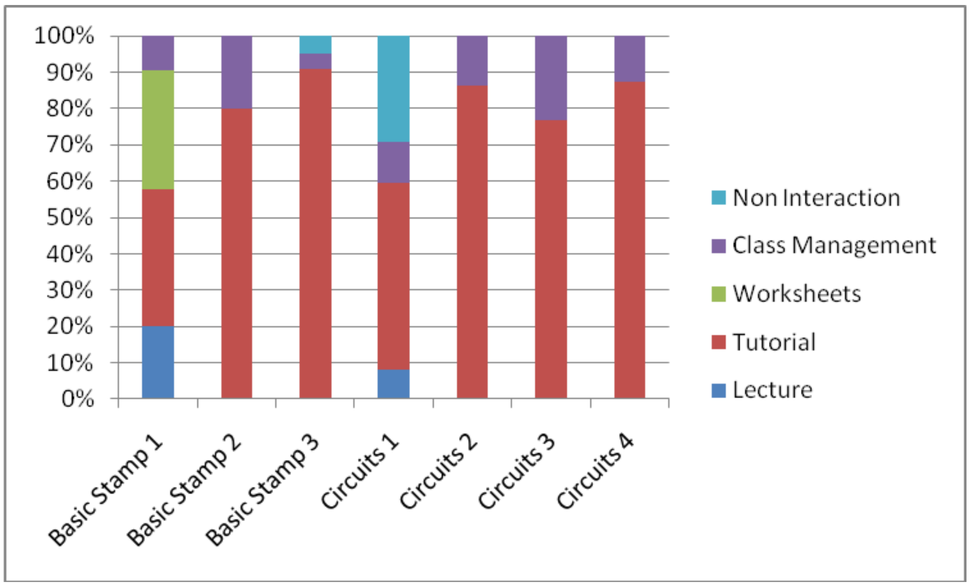
Research Procedure

A single researcher did all of the preliminary clipping and coding of the seven videotaped days in the classroom. Reliability of many of these codes was previously established using multiple coders and computing inter-rater reliability[32]. Clips were first created separately to identify how instruction time was used (in order to code the entire length of the class time). This allowed the researcher to watch the full length of each class session. Next, each lesson was reviewed for the use of mathematics and engineering skills and concepts. In forming the clips and segmenting the classroom videos, the researcher made every attempt to try to isolate single events that captured concepts, skills or interactions whenever possible. However, mutually exclusive coding for single teaching and learning events was not always possible -- sometimes two or more interactions occurred in a single clip because of their intertwined nature. The main mechanism for establishing reliability was included discussions surrounding various codes and how they were applied, allowing consensus to be built around the application of the coding scheme. Secondly, the primary researcher reviewed clips and codes over several passes to ensure that each code was applied properly.

Results and Conclusions

Our research has led to several findings related to our three research questions. First, with regards to how class time is spent, we found that most of the class time (74%) was spent on tutorial, small help sessions with students as they worked with partners or alone to complete projects (see Figure 1). Most of the remaining time was spent on class management (13%) – tasks such as taking roll or handing out materials and supplies, with bits of other activities like lectures (4%) and working on worksheets (5%) thrown in. The teacher interacted with the students almost all of the time, with the exception of a small amount of time (4%) spent off camera. This breakdown is consistent with the subject matter of the DE curriculum, which is focused on project work on a technical level that is well beyond what is otherwise seen in a high school classroom. The level of attention given to the students by the instructor is the highest of any of the three PLTW foundations courses. In the other courses, class management takes a more predominant role (60% in *Introduction to Engineering Design*™ and 23% in *Principles of Engineering*™) as does lecturing (36.5% in the case of *Principles of Engineering*™).

Figure 1: Lesson-wise breakdown of how instruction time is spent over seven hours of Digital Electronics™ classes. Lessons were focused on either working with the basic stamp robot or circuits.



Next, in terms of the division of time spent on skills and concepts, we see an almost equal amount of instruction time spent in both areas, with 41.7% of the total instruction time spent on skills and 34.8% of the total instruction time spent on concepts (see Table 5). We interpret this to mean that students are gaining understandings of both the skills needed to do the work of digital electronics as well as the underlying reasons for the need for the skills. For example, one predominant sequence of tasks that occurred in this study is the creation of circuits. So, as students work to figure out how to move from on-screen circuit simulations developed in the Multisims software to the hardware of wires, LEDS and breadboards, they work on debugging to test their designs and logic. Further, the co-occurrence of skills and concepts occurred far more frequently than the occurrence of a skill or concept on its own. In fact, no concept was covered in the absence of a skill and similarly, skills co-occurred with concepts 83% of the time (Table 5).

Table 5: Code and time summary for instructional time spent on skills and concepts.

Clip coding	Number of clips (N =78)	Clip time (T =2:33:58.5)
At least one skill code	75	2:33:03.8
Skill and no concept codes	21	0:25:51.8
Skill and one or more concept codes	54	2:07:12.0
At least one concept code	55	2:07:51.2
Concept and no skill codes	0	0
Concept and one or more skill codes	55	2:07:51.2

The co-occurrence of mathematics concepts and skills is primarily due to the heavy emphasis on project work. Students are working on projects for over 70% of the total class time observed for this study. Further, the need for integrated engineering skills has been stated due to the nature of digital electronics and the type of projects students are working on.

What is missing, however, is a focus on engineering concepts. Very little emphasis is placed on the design, feedback, analysis and redesign of the final project. Occasionally, the instructor will talk about the engineering cycle as part of design and troubleshooting--for example, how it’s important to be sure wires are placed in an orderly fashion and not knotted up in “spaghetti”, or that an alarm clock has to work properly on all 7 days of the week and even one failure would not be acceptable. In the case of this curriculum, the debugging of circuits is skills-based rather than conceptually based because of this lack of emphasis

Lastly, we found that most of the material presented in this curriculum is explicitly integrated – 77.5% of the time. Due to the nature of the material and the unique subject matter, this was not a surprise. No connections were made 17.6% of the time between the engineering and mathematics. Implied connections were made 4.9% of the time.
Table 6 illustrates where integration occurred within the skills and concepts included in our analysis. Importantly, DE is much more highly integrated than the other foundations curricula both in terms of the number of examples and the amount of class time. In *Introduction to Engineering Design*™, we observed explicit integration 29.4% of the

time[33] and in *Principles of Engineering*™ we see explicit integration 51.8% of the time[34] showing a continuing trend of improvement over the three foundations courses overall with regards to explicit connections.

Calculation of the percentage of integration was accomplished by dividing the total amount of time included in clips coded in each of these categories by the total amount of time coded with a mathematics or engineering skill or concept. Thus, each level of integration's time is divided by the same number, T_{Total} = 2:33:58.5 and N_{Total} = 78, since each clip represents a segment of these categories.

Table 6: Integration of Mathematics and Engineering (Skills and Concepts)

	Explicit Integration Totals : N=49 Time = 1:59:22.6 Percent of Clips (Concepts/Skills): 62.8% Percent of Time (Concepts/Skills): 77.5%				Implicit Integration Totals : N=5 Time =0:07:33.0 Percent of Clips (Concepts/Skills): 6.4% Percent of Time (Concepts/Skills): 4.9%				No Integration Totals : N=24 Time =0:27:02.9 Percent of Clips (Concepts/Skills): 30.8% Percent of Time (Concepts/Skills): 17.6%			
	Time	%Time	# of Clips	% of Clips	Time	% Time	# of Clips	% of Clips	Time	% Time	# of Clips	% of Clips
Math Concepts												
Algebra	0:00:00.0	0.0%	0	0.0%	0:00:48.1	10.6%	1	20%	0:00:00.0	0.0%	0	0.0%
Geometry	0:00:19.5	0.3%	1	2.0%	00:00:00.0	0.0%	0	0.0%	0:00:00.0	0.0%	0	0.0%
Measurement	0:16:14.7	13.6%	4	8.2%	00:00:00.0	0.0%	0	0.0%	0:00:00.0	0.0%	0	0.0%
Number	1:15:30.2	63.2%	29	59.0%	0:03:13.8	42.8%	2	40%	0:00:50.5	3.1%	1	4.2%
Logic	1:57:06.5	98.0%	46	94.9%	0:01:42.7	22.7%	1	20%	0:02:41.5	10.0%	3	12.5%
Mathematics Skills												
Communication	0:00:00.0	0.0%	0	0.0%	00:00:00.0	0	0	0.0%	0:00:00.0	0.0%	0	0.0%
Connections	1:28:10.5	73.9%	33	67.3%	0:04:08.4	54.8%	2	40%	0:00:51.8	3.2%	1	4.2%
Problem Solving	1:40:54.2	84.5%	38	77.6%	0:04:08.4	54.8%	2	40%	0:02:25.9	9.5%	3	12.5%
Reasoning	0:00:59.5	0.8%	1	2.0%	0:02:25.7	32.2%	1	20%	0:00:00.0	0.0%	0	0.0%
Representation	0:51:15.8	42.9%	22	44.9%	0:00:00.0	0.0%	0	0.0%	0:00:00.0	0.0%	0	0.0%

Digital Electronics Project Work

The core basis for PLTW courses is that students must engage in hands-on science learning in order to make concrete connections between the skills and knowledge needed for high technology engineering careers and the academic knowledge imparted in mathematics and science courses. Further, the project based work students complete allows for assessment of student abilities in more than one domain – they demonstrate what they know through the successful completion of projects as well as exams and other written materials. The *Digital Electronics*™ curriculum is especially focused on project-based work – students spent 71.5% of their time in class working on projects as pairs.

Further Details about the Skills and Concepts in the Digital Electronics™ Curriculum

Table 7 details the skill codes and Table 8 illustrates the concept codes that we applied to the individual video clips. We focused only on the coded skills and concepts. In our analysis, a given video clip of a classroom event can contain multiple skill or concept codes as these can be highly integrated in the teacher and students' speech. For this reason, totals can exceed 100%. The second column for both Tables 7 and 8 includes the percentage of the *total number of clips* to which each code was applied (a frequency measure) whereas the third column gives the percentage of the *total amount of class time* to which each code was applied (a durational measure).

As the data in Tables 7 and 8 shows, in this curriculum, there is a balance between the skills and concepts; skills and concepts are difficult to separate from one another and are thus presented in tandem most of the time. As a comparison, in our study of *Principles of Engineering*™, we found a similar balance between class time and the number of clips in which skills and concepts were covered[35]. In these detailed tables, we see that there is a high incidence of mathematics skills such as problem solving, connections and representation. There is a high incidence of engineering skills such as debugging circuits and using computer programs such as Multisims and the basic stamp programming software. In terms of concepts, mathematics concepts predominated. Since DE emphasizes principles of discrete mathematics, the use of logic and the understanding of numbers were frequently observed. This general pattern of relatively light focus on engineering concepts correlates to what we observed in prior studies of the intended and assessed curricula, reported elsewhere[36].

Table 7: Skill Code- Detailed Breakdown.

Skill Category	Skill Code	Frequency of Incidences and Percentage (N = 75)		Amount of Class Time and Percentage (T = 2:33:03.8)	
Mathematics					
	Communication	0	0.0%	0	0.0%
	Connections	36	48.0%	1:33:10.7	60.9%
	Problem Solving	43	57.3%	1:47:55.5	70.5%
	Reasoning	2	2.7%	0:03:25.3	2.2%
	Representation	22	29.3%	0:51:15.8	33.5%
Engineering					
	Understanding Constraints	2	2.7%	0:03:16.3	2.1%
	Choosing Hardware to Build Circuits	7	9.3%	0:14:54.6	9.7%
	Debugging Circuits	39	52.0%	1:21:16.0	53.1%
	Using Multisims (Using Software for Design)	23	2.7%	0:49:28.9	32.3%
	Diagramming Circuits	5	6.7%	0:09:02.9	5.9%
	Using Robotic Command Software	34	45.3%	1:01:21.3	40.1%

Table 8: Concept Code - Detailed Breakdown.

Concept Group	Concept Code	Frequency of Incidences and Percentage (N = 55)		Amount of Class Time and Percentage (T = 2:07:51.2)	
Mathematics					
	Algebra	1	0.02%	0:00:48.1	0.6%
	Geometry	1	0.02%	0:00:19.5	0.3%
	Measurement	4	7.3%	0:16:14.7	12.7%
	Number	32	58.2%	1:19:34.6	62.2%
	Logic	50	90.9%	2:01:30.7	95.0%
Engineering					
	Design	1	0.02%	0:00:19.5	0.3%
	Modeling	1	0.02%	0:01:20.4	1.0%
	Modularity	1	0.02%	0:00:52.6	0.7%

Comparison of Frequencies of Concept Codes and Skill Codes

Since multiple codes are often applied to an individual clip, a comparison of the application of concept and skill codes along with the percentage of clip time devoted to each illustrates where the emphases were in the enacted curriculum. From Table 9, it is clear that engineering concepts are de-emphasized, whereas engineering skills, math concepts and math skills are all given a great deal of attention. As was shown in Table 5, mathematics and engineering are usually presented in tandem so that students are exposed to mathematics ideas and their applications to engineering.

Table 9: Comparison of Engineering Codes vs. Math Codes and Concept Codes vs. Skills Codes

Category	Group	Code	Frequency of Clip Incidence	Absolute Amount of Time and Percentage of Total Clip Time (2:33:58.5)	
Engineering	Engineering Concepts $N_{concept}$ = 3 clips	Design	1	0:00:19.5	0.2%
		Modeling	1	0:01:20.4	0.9%
		Modularity	1	0:00:52.6	0.6%
	Engineering Skills N_{skill} =110 clips	Understanding Constraints	2	0:03:16.3	2.1%
		Choosing Hardware to Build Circuits	7	0:14:54.6	9.7%
		Debugging Circuits	39	1:21:16.0	52.8%
		Using Multisims (Using Software for Design)	23	0:49:28.9	32.1%
		Diagramming Circuits	5	0:09:02.9	5.9%
		Using Robotic Command Software	34	1:01:21.3	39.8%
Mathematics	Math Concepts: N_{skill} = 88 clips	Algebra	1	0:00:48.1	0.5%
		Geometry	1	0:00:19.5	0.2%
		Measurement	4	0:16:14.7	10.6%
		Number	32	1:19:34.6	51.7%
		Logic	50	2:01:30.7	78.9%
	Math Skills: $N_{concept}$ = 103clips	Communication	0	0:00:0.0	0.0%
		Connections	36	1:33:10.7	60.5%
		Problem Solving	43	1:47:55.5	70.1%
		Reasoning	2	0:03:25.3	2.2%
		Representation	22	0:51:15.8	33.3%

How are Mathematics and Engineering Integrated in Digital Electronics?

The science, mathematics and engineering involved in digital electronics are unique in that the integration of this subject matter is inherent in the activities. The creation of the electrical circuit for a particular intent (ex. to make an alarm clock or to simply turn a light on and off) implies an understanding of the logic needed to do so. In DE curriculum students start by creating truth tables and Karnaugh maps of the switches and circuits. They then draw out their circuits using Multisims. Lastly, they wire the circuits on breadboards and debug them, often going back to either the truth tables or Multisims diagrams. Example 1 illustrates how math and engineering concepts can be explicitly integrated during the classroom interactions. Examples of implicit integration and no integration can be found in previous publications[37].

Example 1:

In this example, the students are wiring a digital alarm clock on a breadboard. They designed the circuit in Multisims and are in the process of debugging what they built. In order to create the alarm clock, the student must understand the inputs and outputs, or the logic functions. In lines 3-5 and lines 9-12, the instructor directs the student to the diagram to compare what was figured on paper to what has been built on the breadboard and how to count and integrate each circuit to create a switch.

S: Where are the switches supposed to connect to?

T: See what it says here. These are your ins. Okay. Just go off of this (diagram of circuits). Where's the switch go? Here's your in. So you gotta connect these two legs together. So which ones are those? Let's take number one here.

S: One and two have to be together.

T: (At the same time) So you gotta hook one and two hook together.
And what do you do to that? Then you hook that, to the switch. Make sure your ground is seven. Power is VCC. Count down count up. ‘Kay. Then you got four of 'em. One two three four. Everything's done off identical to that.

S: Okay.

T: So on one integrate circuits one two three four.

S: So you can basically just go off the diagram.

Similarly, when programming a simple robot, such as the basic stamp, students learn to create commands to communicate within a language understood by an electronics instrument. They aren’t creating the circuits, but they are programming them in a way that illustrates their understanding of the order of commands, and the logic needed to make the robot run according to the assigned tasks.

Comparison of the Enacted Curriculum to the Intended and Assessed Curricula

As mentioned previously, the importance of explicit integration cannot be overstated, particularlyfor novice students who are just getting started using highly technical skills and knowledge. This particular course is unique amongst those that we’ve studied in the PLTW sequence in that most of the mathematics in the classroom is explicitly integrated with the engineering activities. These findings are similar to prior work[38], showing a high level of integration in the intended and assessed curricula.

Table 10 shows the analysis of explicit integration across the entire *Digital Electronics*™ intended (idealized) curriculum. Scoring and calculation of the percentage of explicit integration of math concepts for the intended curriculum was accomplished first by identifying the areas of explicit integration in each curricular area (Training, Planning, Activities and Assessments). This was achieved through the comparison of the definition of the curriculum standard with what is presented in the curriculum. One excellent example of explicit integration from the intended curriculum is a unit on binary addition. Students start by learning the basics of binary addition and doing numerous problems in a purely mathematical context. From there they do experimental work that is closely related – implementing different types of adder circuits in their design software and filling in truth tables.

The unit introduces both mathematical and engineering topics and reciprocally uses each one to illustrate the use of the other. In comparing our findings about the intended curriculum, shown in Table 10, to our findings in the enacted curriculum, we can see that similar content and process standards are highlighted and integrated, as expected. Content standards for number, algebra and measurement are well integrated, as are process standards such as problem solving, reasoning, connections and representation. Notably absent in the intended curriculum analysis is logic. Since Boolean algebra is beyond the scope of NCTM standards for grades 9-12, we did not include it in our previous curriculum analyses.

Table 10: Percentage of Explicit Integration of Mathematics Concepts with Engineering Activities in the *Digital Electronics* ™ Intended Curriculum. (For additional information on how these data were generated, see Prevost, et al., 2009).

	Planning (X_p)		Activities (X_{ac})		Assess-ment (X_{as})		Training (X_t)	
	N_p = 132	Percent Integration (X_p/N_p)	N_{ac}= 40	Percent Integration (X_{ac}/N_{ac})	N_{as}=42	Percent Integration (X_{as}/N_{as})	N_t = 26	Percent Integration (X_t / N_t)
Content Standards								
Number	35	17.9	26	65	3	25	67	65.7
Algebra	12	6.2	12	30	1	8.3	37	36.3
Geometry	0	0	0	0	0	0	0	0
Measurement	5	2.6	21	52.5	0	0	53	52.0
Data and Probability	10	5.1	9	22.5	0	0	32	31.4
Process Standards:								
Problem Solving	2	1.0	19	47.5	3	25	49	48.0
Reasoning	6	3.1	22	55	1	8.3	50	49.0
Connection	70	35.9	26	65	5	41.7	85	83.3
Representation	35	17.9	21	52.5	2	16.7	66	64.7
Communication	1	0.5	2	5	2	16.7	2	2.0

Discussion

Skills and conceptual understandings are both important for future success in engineering careers and for academic achievement in STEM fields. We have investigated how such understandings play out in the day-to-day, minute-to-minute interactions during class lessons. Our findings from analysis of seven hours of lessons in the PLTW *Digital Electronics*™ curriculum have led us to: (1) understand better how time is spent in the classroom; (2) understand how students work to accomplish the projects in this unique curriculum; (3) analyze the application of mathematics and engineering skills and concepts in the classroom; and (4) analyze and quantify the explicitness of the connections that are made within the mathematics and engineering subject matter. We also observe that the projects used in *Digital Electronics*™ allow students to gain experience using both math and engineering knowledge.

Our observations of how course material is presented in the classroom combined with our prior work on the curricular materials and evaluations allows us to gain insight into what is happening in the high school pre-engineering classroom. Our consideration of the integration of academic and technical aspects of the curriculum has helped us to notice a pattern that has emerged from the PLTW program. We observed that as students move through the curricula across the three foundations courses, the focus shifts from a low level of explicit connections between academic materials and engineering skills and concepts to a much higher level of integration. This explicit connection grounds students' conceptual knowledge to applications and allows them to generalize the technical knowledge they gain and apply it to novel settings. We believe that this study and its companion pieces will raise awareness of the nature of classroom learning and for the need for explicit integration amongst practitioners.

Together with prior research[39,40,41], extending over 14 hours of classroom learning that we have now analyzed ,we illustrate that higher level courses are more integrated. This must we weighed in relation to the needs of students and the aims behind K-12 engineering education. With the goals of getting more students interested in engineering careers and able to perform at academic levels that would enable them to realize a career in a STEM field, we must consider the need to achieve a higher level of integration earlier in the curriculum sequence.

As the emphasis of high technology careers in the STEM fields continue to grow in importance for high school students, we look to curricula like PLTW as models for what can be done in the classroom. Through the work of curriculum analysis, we can better understand what opportunities students have to engage with core subject matter in applied situations. Further, this work can be used in future studies to understand the nature of K-12 engineering education and instruction, and point to ways teaching and learning can be improved.

This work has provided us with some rich information, but it has some notable limitations that we address here. First, we provide only a snapshot of the enacted curriculum – one classroom and seven lessons. Thus we cannot possibly make claims about what happens in every classroom. The nature of classroom video analysis is quite time intensive, and always selective. Thus, there are even things omitted from the classrooms we observed. However, the body of evidence we are gathering will allow us to continue developing our knowledge about how engineering is taught in K-12 settings. Second, our coding system represents only one accounting for the events that were studied in the classroom. It is very interesting to look into the classroom and see the real circumstances that high school teachers and students encounter. Based on these current findings, we are encouraged by the progression of the level of integration throughout the PLTW foundations sequence and particularly with the *Digital Electronics*™ course. We invite others to explore the nature of classroom learning and instruction, for we believe that this research has a great deal to contribute to improving curriculum design, teachers' instructional practices and policy discussions on pre-college engineering.

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