AC 2009-1577: CLASSROOM LEARNING AND INSTRUCTION IN HIGH SCHOOL PRE-COLLEGE ENGINEERING SETTINGS: A VIDEO-BASED ANALYSIS

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Dr. Nathan's research is largely rooted in cognitive, embodied and social perspectives on learning and instruction, and employs quantitative and qualitative methods. Currently, he examines the intersection of student and teacher cognition as it plays out in classroom learning situations, primarily involving middle and high school mathematics, science and engineering. His research on students' reasoning showed that they may invent effective strategies and representations for solving math problems, and these methods can serve as bridges for instruction. He is also exploring the embodied nature of students' knowledge, as exhibited by gestures, and the mediating effects of action on conceptual knowledge. His studies of teachers' beliefs about the development of students' mathematical reasoning showed that content experts can show evidence of expert blind spot, which influences teachers' expectations of what makes things difficult for their students.

He is currently co-principal investigator for the AWAKEN Project (funded by NSF-EEP), which examines the nature of high school pre-engineering, early college engineering, and professional engineering practice in order to foster a more diverse and more able pool of engineering students and practitioners.

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Classroom Learning and Instruction in High School Pre-College Engineering Settings: A Video-Based Analysis

Abstract

We report on descriptive analyses of classroom observations of the instruction and classroom interactions that took place over four days of a high school pre-engineering class, *Project Lead the Way*, as participants engaged in project-based learning. Our objective was to study the *enacted curriculum* and determine how class time was apportioned, the extent to which time was distributed between developing technical skills and fostering conceptual understanding in engineering and mathematics, and the degree to which mathematics concepts were implicitly embedded within the engineering activities or made explicit for students, and therefore more supportive of transfer of learning.

Our coding of the video data support the following three main descriptive results: (1) more of the instructor's time was spent on class management (non-instructional) tasks than on any other classroom activity, (2) a greater proportion of the total observed instruction time was devoted to skills rather than concepts, and (3) only a small fraction of instruction that linked math concepts to engineering coursework made those links explicit, while the large majority were implicitly embedded in the activities and the CAD software used in the class. Both positive and negative examples of explicit integration are provided to illustrate these events. We relate these results to prior research on the *intended* curriculum used to convey the idealized pre-engineering program, and discuss the implications these findings have for fostering deep learning of engineering concepts and supporting the transfer of knowledge to novel tasks and situations.

Introduction

Engineering excellence in the US serves as one of the primary vehicles for technological innovation, economic prosperity, national security, and advancements in public health. However, current educational trends portend a decline in these areas as the mathematical and scientific preparation of American K-12 students slip in relation to other industrialized nations, and students opt out of engineering programs and careers[1]. Interest in science, mathematics, and technology is particularly low among disadvantaged groups that have been underrepresented in those fields[2]. 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.

The central objective of this paper is to explore the extent to which integration of mathematics ideas with engineering is evident during classroom learning and instruction. We present a descriptive study of classroom learning and instruction. Preliminary to the empirical findings, we review the basis for this integrative approach in educational policy, contemporary learning theory, and as it is intended within a widely adopted pre-engineering curriculum program, *Project Lead the Way*.

Pre-Engineering as an Integrative Curriculum

In *Rising Above the Gathering Storm*, the National Research Council[3] calls for educational leaders to optimize the knowledge-based resources and energize the STEM career pipeline. The report repeatedly emphasizes the importance of science and math achievement as a precursor for technical advancement, and relates the poor international showing of US students in math and science to the declining impact of the US in research, patent issuance and economic and technological standing.

The primacy of math and science to engineering is a common view that can, in educational settings, at least, clash with the objectives of engineering. The Nobel laureate Herbert Simon[4] observed in the late 1960's that "Engineering schools gradually became schools of physics and mathematics; medical schools became schools of biological science, business schools became schools of finite mathematics" (p. 111). As Cajas[5] noted, this is still true decades later:

> The way in which future technologists (e.g., engineers or medical doctors) are generally prepared is the following: Students first take science classes with the assumption that such classes can be applied to specific technological problems (e.g., engineering problems, medical problems). The justification of taking science classes (physics for example in the case of engineers or physiology in the case of medicine) is that these classes are the bases of their future professional work (p. 5).

While the relation of math and science to engineering in this report is generally presented as unidirectional, we need to keep in mind their mutual relationship. For engineering design and development can drive scientific and mathematical advancement as well[6,7]. For example, advances in areas like xerography for photocopying preceded scientific understanding electrophotography. Thus, the bidirectional influences of science and math with engineering, so central to technological innovation, must be recognized as vital to a rigorous, high quality engineering educational program.

Conjointly, the push for an integrative curriculum for vocational and technical education comes from laws and policies for K12 education. The reauthorization of the Perkins Vocational Education Act mandated that technical education and academic math and science topics must be integrated so "students achieve both academic and occupational competencies." In particular, mathematics is recognized for its singular importance for modeling and generalization[8].

Explicit Integration as a Critical Component to Learning for Transfer

Transfer refers to the ability of a learner to generalize what is learned from the initial training conditions to novel tasks. When there are demonstrable benefits from prior experience, such that the time to reach proficiency is measurably shorter or the conceptual understanding demonstrably deeper with the prior experience than without, psychologists report the occurrence of positive transfer. Bransford and Schwartz[9], in their review of transfer research, make clear the central importance of transfer to the educational system: "A belief in transfer lies at the heart of our educational system" (p. 61). This is because it is simply not possible to expose students to every type of task and every situation in which their learning may apply. As a matter of course, educators sample among the vast expanse of possible problems and scenarios, selecting central and exemplary topics and applications, with the intention (and hope!) that these select experiences will generalize broadly.

Yet, from the earliest studies of transfer within experimental psychology, scholars have documented the limits of transfer. Thorndike's work[10] showed that while people may do well when tested on the specific content that they practiced, they do not always transfer that learning to a new situation. As Thorndike and others have argued (e.g., Singley & Anderson[11]), transfer occurs in direct proportion to the degree to which the novel situation matches the training conditions. In fact, when the match is very close, we do not even recognize it as transfer, but merely the application or testing of the initial learning experience.

But learning theory has progressed beyond simply examining the degree of surface similarity between training and testing to gauge transfer. Two important insights have emerged in the ensuing century about how to foster transfer. First, transfer is facilitated when learners develop a conceptual (sometimes called "deep") understanding of the material. This is because knowledge needs to be organized around central ideas in order to facilitate its acquisition and application[12]. As evidence of this, Judd[13] contrasted two conditions under which students learned to successfully throw darts at underwater targets. Students were allowed to achieve a high level of mastery. Students who only practiced the skill of hitting the target showed poor transfer when the water level was changed. But those who practiced and also learned specifically about the theory of index of refraction were able to more successfully adjust their aim. Similarly, Wertheimer[14] showed that students with a shallow understanding of the procedure for calculating the area of a parallelogram were confounded when they could no longer drop an altitude within the bounds of the polygon. In contrast, those who understood conceptually that they were regrouping areas of the parallelogram to form a rectangle of equal area were much more flexible in solving a range of different problems.

A second insight is that transfer is aided when one's knowledge of the concepts is explicitly integrated with the application area. Palincsar and Brown[15,16] demonstrated this by developing a program to improve reading comprehension, called *Reciprocal Teaching*. Learners with difficulties in reading comprehension were trained to use strategies that were commonly used by highly competent readers: summarizing, questioning, clarifying, and predicting. Through practice they developed facility with these important skills and exhibited immediate improvements in comprehension. Yet over time, these advantages declined because the successful strategies fell into disuse. Students introduced to the strategies along with ritualized participant structures that explicitly identified and integrated the practices into students' normal reading routines showed sustained gains in comprehension. Examples of explicit integration of concepts and strategies can also be found in science and math learning (e.g., Brown, Bransford, Ferrara & Campione[17]; CTGV[18]; Schoenfeld[19]; White & Fredrickson[20]). As Bransford and Schwarz[9] note, ideally, tests of transfer "explore people's abilities to learn new information and relate their learning to previous experiences" (p. 70).

As further support for the positive impact of making explicit conceptions, Stone, Alfeld, and Pearson[21] showed the benefits for a professional development and curriculum re-design program that improves the mathematics performance for students participating in high school technical education programs (agriculture, auto technology, business and marketing, health, and information technology). Experimental group teachers worked with content specialists to explicitly integrate mathematics concepts into the pre-existing curricula. Over one year, students who otherwise tend to show poor performance on a number of standardized math assessments showed statistically significant gains in math over and above control group participants, but without any apparent loss in their technical skills development. Though the study did not examine the effects on pre-engineering courses, it provides an important positive example of both the manner of providing enhanced mathematics learning within existing technical education courses, and the substantive benefits of doing so.

In sum, Cognitive Science research on transfer emphasizes three central points. Transfer to a novel task or situation is related to the similarity it has with the training situation. Transfer is facilitated when learners develop a conceptual understanding of the ideas that are to be transferred. And the likelihood of transfer increases when the integration of new concepts with one's prior experience and knowledge is made explicit to the learner. These ideas serve to guide our analysis of the nature of the observed classroom instruction.

Project Lead the Way *as an Exemplary Pre-Engineering Curriculum*

For this study of classroom learning and instruction, we chose to focus on *Project Lead the Way* (*PLTW*). *PLTW* provides both middle school and high school curriculum programs. The middle school program, *Gateway to Technology*, is divided into five independent nine-week courses for grades six through eight. The high school engineering program, *Pathway to Engineering,* is a four-year, pre-engineering curriculum that is intended to be integrated into the students' academic program of study. It offers seven high school courses accredited for college credit. Our focus is on the high school program, and we refer to this program throughout simply as *PLTW*. The high school pre-engineering program has been adopted by over 15% of US high schools, and is present in all 50 states. Thus *PLTW* is a widely adopted program, and findings from our study of *PLTW* use in the classroom have far-reaching implications. *PLTW* is also affiliated with over 30 nationally accredited colleges of engineering, such as Rochester Institute of Technology, Duke, San Diego State, and Purdue[22]. *PLTW* also explicitly strives to integrate students' college preparatory and technical education programs of study[23]:

> *PLTW*'s premier high school program, Pathway To Engineering™, is a four-year course of study integrated into the students' core curriculum. The combination of traditional math and science courses with innovative Pathway To Engineering courses prepares students for college majors in engineering and E/T fields and offers them the opportunity to earn college credit while still in high school.

Indeed, the NRC report, *Rising Above the Gathering Storm* explicitly identifies *PLTW* as a model curriculum for providing the kind of rigorous K-12 materials needed to improve math and science learning and increase America's technological talent pool. Given the broad market penetration, affiliation with institutions of higher education, including provisions for college credit, and commitment to an integrated program across academic and technical education curricula, *PLTW* is an important exemplar for studying the degree to which integrated, and conceptually based pre-engineering programs are implemented in public high school classrooms.

Prior Research on the Integration of STEM Concepts in Pre-Engineering Curricula

Previously, investigators in two studies have provided analytic accounts of the math, science and engineering concepts that are presented in the curriculum materials of *PLTW* and other K-12 pre-engineering programs[24,25]. Both were studies of the idealized, or *intended* curriculum, and therefore address only the static plan that is put forth in the printed materials used for the course.

Although conducted separately, and with different objectives, these curriculum analyses provided some remarkably similar findings. In their analysis of the *PLTW* high school *intended curriculum*, Nathan and colleagues[24] examined the absolute and relative frequency with which *PLTW* addresses the mathematics standards (as obtained from the National Council of Teachers of Mathematics[26]) in its three core courses (*Introduction to Engineering Design, Principles of Engineering,* and *Digital Electronics*), and compared this to the mathematics curricula that high school students experience concurrently in their academic courses. The study distinguished between content standards and process standards. Math *content standards* are the topics of math, including: numbers and operations; patterns, functions, and algebra; geometry and spatial sense; and measurement. Math *process standards* address, in complimentary fashion, how math is performed and how math knowledge is created, verified, and disseminated, including: methods of data analysis; problem solving; reasoning and proof; communication; connections made across fields of mathematics and applications outside of math; and ways of representing mathematical relationships. The results of this comparative curriculum analysis show that the pre-engineering *PLTW* curriculum addresses far fewer math content standards than are addressed by the academic math courses taken by the students in the same district. Subsequent analyses of the *PLTW* core curricula, as well as teacher training materials and course assessments, show limited occasions where the mathematics concepts that do arise are explicitly integrated with the engineering activities intended for each lesson[27]. *PLTW* courses do a much better job addressing process standards, particularly problem solving and uses of representations.

In another curriculum analysis, Welty and colleagues[25] took a broader view, though obtained less detail about any one program. They analyzed twenty-two pre-K-12 pre-engineering curricula, including nine high school programs. The analysis explored the mission and goals of each curriculum; the presence of engineering concepts; and the treatment of mathematics, science, and technology. The investigators offer only preliminary findings at this point. However, their remarks to date are most striking about the shallow role of mathematics across the corpus of curricula. In findings that echo the Nathan et al.[24] study of *PLTW*, Welty and colleagues[25] lament "the noticeably thin presence of mathematics" in K-12 engineering curricula (p. 10). They explained, "Most of the mathematics in engineering curricula simply involved taking measurements and gathering, organizing and presenting data. Very little attention was given to using mathematics to solve for unknowns. Furthermore, little attention was given to the power of mathematical models in engineering design" (p. 9).

Research Questions

Curriculum can be divided into the intended, enacted, assessed, and learned curricula (e.g., Porter[28]). The *intended curriculum* typically includes the printed course materials and other closely connected resources (manipulatives, software, etc.) as well as national and state curriculum standards, which specify the grade-specific objectives for what each student must know and be able to do. In this sense, analysis of the intended curriculum provides a static picture of the course. 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. Analyses of the intended or idealized curriculum paint a foundational but incomplete picture of a course that gives so much attention to in-class group project work. The current investigation complements and extends previous analyses of the intended *PLTW* curriculum (texts, training materials, assessments, and other instructional materials) by turning to the *enacted* curriculum as it is implemented in specific schools and classrooms. For the purposes of this study, we focus on the foundations course "Introduction to Engineering Design." This is the course taken most often by high school students in two studies of district-wide technical education course enrollment[29,30].

Analysis of the enacted curriculum provides an inherently richer account than the intended curriculum since its object of focus is the actual teaching and learning behaviors and student-teacher and student-student interactions. Consequently it is necessary to work from primary observations in the field and videotaped records to determine the events and interactions that occur in the course of teaching and learning. Classroom observation is an especially important methodology given the practical nature of this course and the emphasis on project-based work and peer collaboration.

Our analyses of the classroom video data is motivated by three research questions:

1. **How is class time apportioned?** Specifically, we are interested in how time is distributed between teacher-centered instruction, teacher-directed tutoring of teams or individuals, student-directed collaboration, and administrative (non-instructional) tasks.

2. **What is the emphasis on promoting conceptual understanding?** Specifically we examined the portion of class time spent on concepts that are central (as determined by national and state standards) to STEM education, as compared to time spent on technical skills involved in engineering and mathematical activities.

3. **What is the emphasis on explicitly integrating students' conceptual understanding?** Specifically, we sought to determine the frequency with which math concepts arose during the lessons we observed, and how often these concepts were *explicitly* integrated (as opposed to being implicitly embedded) with the engineering activities and lessons that were the focus of the class.

Data and Methodology

We report here on findings from our quantitative/qualitative analysis of video data from four *PLTW* "Introduction to Engineering Design" lessons on three separate days at one of our observation sites, a large urban high school that offers several different *PLTW* courses. The actual lessons we observed took place during a unit in which students measured and reproduced in a CAD environment small robotic vehicles or other model made of Legos™. Each lesson lasted approximately 50 minutes.

First, the videotapes were digitized and entered into Transana (Fassnacht & Woods[31]; see www.transana.org), a computer application for discourse analysis that integrates the video, transcript text and researcher codes. Classroom talk was divided into segments we called *clips*, and clips were coded to reflect the points of interest in the research questions listed above.

Coding Framework

The coding framework for our qualitative/quantitative analysis delineates three different dimensions:

A. *Instruction time* codes subdivide each class period based on how the instructor interacts with students.
B. *Concepts* mark engagement with "big ideas" from STEM, such as modularity in engineering, projection in mathematics, and Newton's laws in physics. We separately note whether the math concepts are explicitly integrated during instruction.
C. *Skills* address process-oriented tasks that may not require conceptual understanding but are important for doing practical engineering work.

We discuss each dimension below and comment as necessary on the relevance of each dimension to our research questions and to briefly describe member codes.

Instruction time

The instruction time code group allows us to characterize how the instructor allocates class time during a particular lesson. This code is directly relevant to our first research question and stands to shed light on what a typical day of *PLTW* instruction "looks like." The codes and their descriptions for this data dimension are given in Table 1.

Table 1: Codes for instructional time.

Code	**Description**
Lecture	Teacher is engaged in large-group instruction, including lecture-style teaching and demos with 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.
Class management	Teacher is engaged in administrative, disciplinary, or other non-instructional tasks, including collecting homework, etc.
Non-interaction	Teacher is not interacting with students and may be grading, doing prep, conferring with colleagues, etc.

Concepts

Concept codes identify segments of class time that revolve around the central organizing ideas from mathematics and engineering[12]. The individual codes in this group, shown in Table 2, accumulated via both top-down theoretical concerns and bottom-up observations; that is, in some cases we included codes that reflect important concepts identified in various scholarly[32], regulatory/professional[33,26], and popular[34] accounts of the study and practice of engineering, and in other cases we identified additional concepts by watching the videos themselves. In particular, we included codes for all of the concepts in the "content standards" from the National Council of Teachers of Mathematics *Standards for School Mathematics*[26] in order to facilitate comparisons with our group's past work on the embedded mathematics in the published *PLTW* curriculum.

In some cases, the content of the lessons we observed suggested quite specialized codes (e.g. Geometry: Curvilinear surfaces). We expect similar specialized codes to emerge in all categories as we continue to observe a more diverse set of lessons. Note that, for brevity's sake, we have included only those engineering concept codes that were actually applied to at least one clip in this dataset.

Note also that we applied an additional code to any clip coded for math concepts indicating whether or not that concept was explicitly integrated into the surrounding engineering or technology lesson or merely implicitly embedded. See the results section for a more detailed discussion of how we made this distinction, along with a classroom example of a positive and negative instance of this explicit integration.

Skills

Skills codes are distinct from concept codes in that they identify process-based competencies (methods and procedures) rather than structurally organizing ideas in math, science, and engineering. Skills are, of course, a central aspect of engineering learning and competency[8]. To choose an example that is relevant to our dataset, we point out that a student could perhaps learn to use CAD software to create 3D representations of engineered parts without learning any of the analytical geometry concepts that underlie this software. These categories and codes, shown in Table 3, were also chosen with respect to both theoretical ideas about the kind of skills *PLTW* students will learn and concrete skills we actually observed them learning.

Table 2: Concept codes.

Category	Code
Math: Geometry	Curvilinear surfaces
Math: Geometry	Projection
Math: Geometry	Reference planes/lines/points
Math: Algebra	Algebra
Math: Data/probability	Data/probability
Math: Measurement	Measurement
Math: Number	Intersection (set theory)
Engineering	Functional analysis
Engineering	Modeling
Engineering	Modularity
Engineering	Structural analysis

Table 3: Skill codes.

Category	Code
Math: Geometry	Dimensional arithmetic (adding, subtracting distances)
Math: Geometry	Deducing angles (with trigonometry, etc.)
Math: Measurement	Calipers
Math: Measurement	Depth gauge
Engineering: CAD	Dimensioning
Engineering: CAD	Enforcing conventions
Engineering: CAD	File management
Engineering: CAD	Object creation/alteration/manipulation

Research Procedure

A single researcher performed the initial clip making and coding of the four videotaped lessons. Clips were made to capture event units in the classroom, and strike an acceptable balance between clip length and clip cohesiveness. Every code, including ones for which no skill or concept code applied, received exactly one instruction time code, reflecting the mutual exclusive nature of these categories. Clips were also established to try to isolate single concepts, skills or interactions whenever possible. However, mutually exclusive coding for concepts and skills was not possible -- sometimes two or more skill and/or concept codes were applied to a single clip because of their intertwined nature. Where possible, codes that frequently co-occurred were merged to simplify the coding system. The result was that very few overlapping codes were in the final data set.

There were two mechanisms for providing feedback and establishing reliability for the coding process. First, after the initial lesson was completely clipped and coded, the research team discussed the choice of codes and strategies for applying them consistently. After incorporating that feedback (including renaming some codes and recoding some clips), the original researcher clipped and coded the remaining three lessons. Once the first coding pass was complete, a second researcher coded a reliability test set of fifty randomly selected clips (22.0% of the sample by number of clips, 20.3% by time). The two researchers then discussed the clips for which their coding disagreed and came to a consensus on how those particular codes should be redefined and applied. The first researcher then documented the revised definitions and updated the clips to which those codes had been applied, reflecting the changes identified during this inter-rater reliability exercise.

Results and Conclusions

Our coding of the video data support the following three main descriptive results: (1) more of the instructor's time was spent on class management (non-instructional) tasks—especially collecting and grading team project work—than on any other classroom activity, (2) a greater proportion of the total observed instruction time was devoted to skills than to concepts, and (3) only a small fraction of instruction that linked math concepts to engineering coursework (science concepts were absent in these lessons) made those links explicit.

Predominance of class management

Figure 1 shows that class management tasks tended to dominate the instructor's time over the four lessons in the dataset. Of course, it's important to note these four lessons represent a small fraction of the *PLTW Introduction to Engineering Design* curriculum, so we cannot know for sure whether the patterns we observed held in general for this particular course at this particular site, let alone at any others. Subsequent studies with a greater number of observations across a range of classroom will ultimately be needed to establish the reliability of these findings.

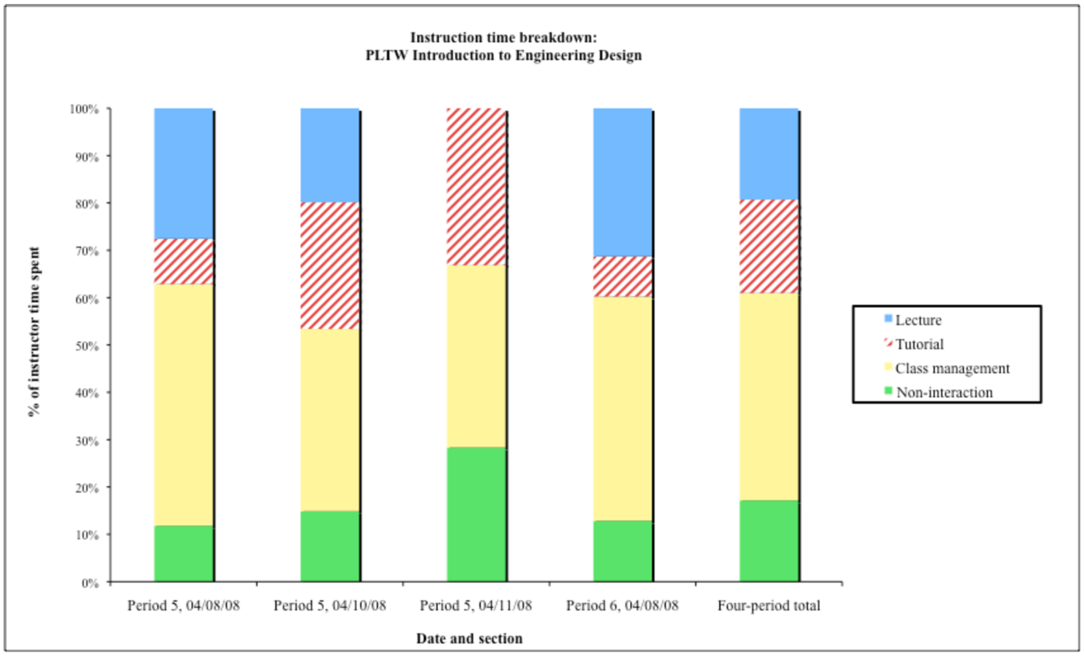

Figure 1: Lesson-wise instruction time breakdown for the four *PLTW Intro to Engineering Design* lessons observed in April 2008.

These data point out one of the drawbacks of the project-based approach: realistic engineering projects involve a great deal of record keeping and take a long time to collect and grade, which is what the instructor was doing during much of the time coded as class management. Of course, students were still working in groups or individually during most of this time, so it's not as if this time was wasted. However, the technological and administrative burden associated with checking in many complex designs per student per project is, if nothing else, important to note and characterize, as we have done here.

Predominance of Skills over Concepts During Instruction

Second, across the combined topics, almost four times more instructor contact time was devoted to skills (roughly 73 minutes spread over 93 clips) than concepts (roughly 26 minutes spread over 48 clips). Table 4 summarizes these results. Note that in Table 4, the four Skills and Concepts categories are neither mutually exclusive nor exhaustive of the total number of clips. For this reason, we also wanted to show the extent to which both skills and concepts were taught "in isolation" and in tandem. We see that 60 of 93 clips (64.5%) that were coded as skills instruction were not also coded as concept instruction. A much smaller proportion, 15 of 48 clips (31.25%), of clips coded as concept instruction was not also coded as skills instruction. This pattern could indicate a (presumably desirable) tendency to associate conceptual material with relevant skills (68.75% of the time) rather than teaching decontextualized concepts in the abstract. The preponderance of skills-only instruction could also indicate a (potentially undesirable) tendency to stress procedure-based "how-to" type instruction over more fundamental material. As noted, cognitive science research shows this is a common profile, but can detract from successful transfer. We also observed a large proportion of instructional time (nearly 2 hours and 6 minutes, out of 3 hours and 23 minutes, or 61.9%) that addressed neither skills nor concepts.

The next set of tables present a more detailed accounting of each of the skills (Table 5a) and concept codes (Table 5b) that the coders actually applied to the individual video clips. Here we focused only on the coded skills and concepts. We note that a given video clip of a classroom event can contain multiple skills or concept codes. For this reason, totals can exceed 100%.

We first note the absence of science-specific concepts and skills present in this data set. Because of the emphasis on 3D modeling, measurement and computer-aided design, actual concepts from the physical sciences were not addressed. Besides the larger percentages found among several of the skill code groups, we also draw the reader's attention to the two different metrics used in both Tables 5a and 5b by which we measure the occurrences of class events. The first pair of numerical columns presents the absolute frequencies and percentages of the *total number of clips* to which each code was applied whereas the second pair of columns gives the time duration (in seconds) and percentage of the *total amount of class time* to which each code was applied. Discrepancies between these two measures may suggest the relative ubiquity or complexity of a given skill or concept to the subjects of these days' lessons. For instance, a relatively high percentage in the first column pair and a relatively low one in the second column pair would suggest that the skill or concept comes up a lot in class but is relatively straightforward to cover, whereas the converse could indicate a skill or concept that doesn't come up very often but is more involved to explain or apply. Finally, we note that certain skills and concepts that are interrelated will show correlations of frequency. For instance, when the instruction addressed the skills involved with "Object Creation/ Alteration/Manipulation" (a very common activity that drew on the CAD software that was central to much of the course curriculum) the related concepts "Modeling" and "Modularity" also tended to co-occur, which explains why the frequencies of these codes tended to parallel each other.

Table 4: Code and time summary for instructional time spent on skills and concepts.

Clip coding	Number of clips (N = 212)		Clip time (T = 3:23:17)	
At least one skill code	93		1:13:06	
Skill and no concept codes		60		0:51:03
Skill and one or more concept codes		33		0:22:03
At least one concept code	48		0:26:17	
Concept and no skill codes		15		0:4:15
Concept and one or more skill codes		33		0:22:03
No Skill or Concepts Codes	104		2:05:56	

Table 5a: Skill code detailed breakdown.

Skill Group	Skill Code	Frequency of Incidences and Percentage (N = 93)		Amount of Class Time and Percentage (T = 1:13:06 or 4386 sec)	
Engineering Skills: CAD	Dimensioning	21	22.6%	901.5	20.6%
	Enforcing Conventions	5	5.4%	61.4	1.4%
	File Management	26	28%	1404.1	32%
	Object Creation/ Alteration/Manipulation	49	52.7%	2541.4	57.9%
Math Skills: Geometry	Deducing Angles	1	1.1%	35.4	0.8%
	Dimensional Arithmetic	1	1.1%	16.7	0.4%
Math Skills: Measurement	Measurement Calipers	1	1.1%	33.7	0.8%
	Measurement Depth Gauge	1	1.1%	18.3	0.4%

Table 5b: Concept code detailed breakdown.

Concept Group	Concept Code	Frequency of Incidences and Percentage (N = 48)		Amount of Class Time (sec) and Percentage (T = 0:26:17 or 1577 sec)	
Engineering Concepts	Functional Analysis	1	2.1%	8.9	0.6%
	Modeling	9	18.8%	252	16%
	Modularity	11	22.9%	418.5	26.5%
	Structural Analysis	1	2.1%	7.9	0.5%
Math Concepts: Geometry	Curvilinear Surfaces	3	6.3%	107.8	6.8%
	Projection	7	14.6%	356	22.6%
	Reference Planes/Lines/Points	7	14.6%	233.5	14.8%
Math Concepts: Measurement	Measurement	7	14.6%	225	14.3%
Math Concepts: Number	Number	9	18.8%	276.7	17.5%
	Set Theory	1	2.1%	28.8	1.8%

Table 6: Engineering and math code detailed breakdown

Engineering or math?	Group	Code	Frequency and Percentage of Clip Incidence		Absolute and Percentage of Class Time	
Engineering $N_{Total} = 104$ $T_{Total} = 4529.3$	Engineering Skills $N_{skill} = 91$ $T_{skill} = 4333.6$ s	Dimensioning	21	20.2%	901.5	19.9%
		Enforcing Conventions	5	4.8%	61.4	1.4%
		File Management	26	25.0%	1404.1	31.0%
		Object Creation/ Alteration/Manipulation	49	47.1%	2541.4	56.1%
	Engineering Concepts $N_{concept} = 22$ clips $T_{concept} = 687.3$ s	Functional Analysis	1	1.0%	8.9	0.2%
		Modeling	9	8.7%	252	5.6%
		Modularity	11	10.6%	418.5	9.2%
		Structural Analysis	1	1.0%	7.9	0.2%
Math $N_{Total} = 30$ $T_{Total} = 1035.8$	Math Skills: $N_{skill} = 4$ $T_{skill} = 104$ s	Deducing Angles	1	3.3%	35.4	3.4%
		Dimensional Arithmetic	1	3.3%	16.7	1.6%
		Measurement Calipers	1	3.3%	33.7	3.3%
		Measurement Depth	1	3.3%	18.3	1.8%
	Math Concepts: $N_{concept} = 29$ $T_{concept} = 1002.15$ s	Curvilinear Surfaces	3	10.0%	107.8	10.4%
		Projection	7	23.3%	356	34.4%
		Reference Planes/Lines/Points	7	23.3%	233.5	22.5%
		Measurement	7	23.3%	225	21.7%
		Number	9	30.0%	276.7	26.7%
		Intersection (Set Theory)	1	3.3%	28.8	2.8%

NB. Totals will not add to 100% because events can have multiple skills and concepts codes.

Across all areas of instruction, occurrences of skills code predominated. However, the relative frequency and time spent on skills and concepts as they are shown in Tables 4, 5a and 5b can be seen in a different light when one looks at the proportion of concepts and skills disaggregated by engineering and mathematics domains. As Table 6 makes clear, when instruction focused on engineering topics, skills were emphasized over concepts, and occupy the majority of the lessons, whether measured by frequency of video clips (101 clips contained one or more skills versus 22 concepts clips), or class time. However, the opposite pattern was evident when the focus was on mathematics instruction; here, the concept codes were more frequent than skills codes (34 clips contained one or more concepts versus 4 skills clips), and occupied more time within those instructional events. This illustrates that engineering instruction over these class observations was generally procedural whereas mathematics instruction, though constituting a relatively only a small portion of the classroom events, was more likely to emphasize conceptual aspects.

Relative Lack of Explicit Integration

Lastly, we discuss perhaps the most significant finding to come out of this analysis: The relative lack of explicit integration of math and science concepts present in the lessons we observed. As previously noted, all the video clips in the dataset containing math concepts (none were coded as science concept instruction) were coded as to whether the concept discussed was *explicitly integrated* to the engineering activity or lesson in some demonstrable way or merely alluded to or mentioned. This was driven in part by findings from the cognitive science literature on the role of explicit integration for successful transfer[9,15]. This idea of explicitness of the underlying mathematics content was also central to the success demonstrated by Stone, Alfeld, and Pearson's study[21] of improving math achievement through its integration into other types of career and technical education courses[21].

While we did not require an explicit appearance of a mathematic formula or the like in order to mark a concept as explicitly integrated (although an overt discussion of a mathematical formula or theorem would certainly qualify), we did require that the instructor, student, or technical resources (such as the CAD software) in some way signal that the concept under discussion *was* in fact a mathematics concept. To clarify our coding criteria, we present below two prototypical examples of the kinds of classroom scenes that were and were not coded as examples of explicit conceptual integration of mathematics.

The most common instances in which math concepts remained implicit took place when the CAD software performed the mathematics "automatically" for the student. This seems to encourage both students and the instructor to refer to a particular concept or procedure in terms of the software operation, without identifying it as explicitly mathematical or make the connection to students' prior mathematical learning experiences.

One of the most common concepts in these lessons was *geometric projection*. Frequently, a feature of some surface in the CAD environment would need to be projected to another surface for use as a reference point, line, or plane. The example excerpt shows a portion of the instructor's demonstration-based lecture at the beginning of one of the class periods. The task at hand is to create a CAD representation of a single Lego piece ("unit cell") that can be replicated to form individual Lego blocks; where one of the steps in creating this piece requires a projection-like task. Here, the math concept of geometric projection is clearly embedded within the activity being performed by the CAD software, AutoDesk. However, there are several signals that what both the instructor and students are directly referring to is *not* the math concept of projection at all, but a feature of the software (called "Project Geometry") that performs an internal representational task requiring geometric projection. To enhance the reader's appreciation of these events, we have annotated the transcript within square brackets to provide addition information that might only be available from watching the video, or valuable background information about the class or the software.

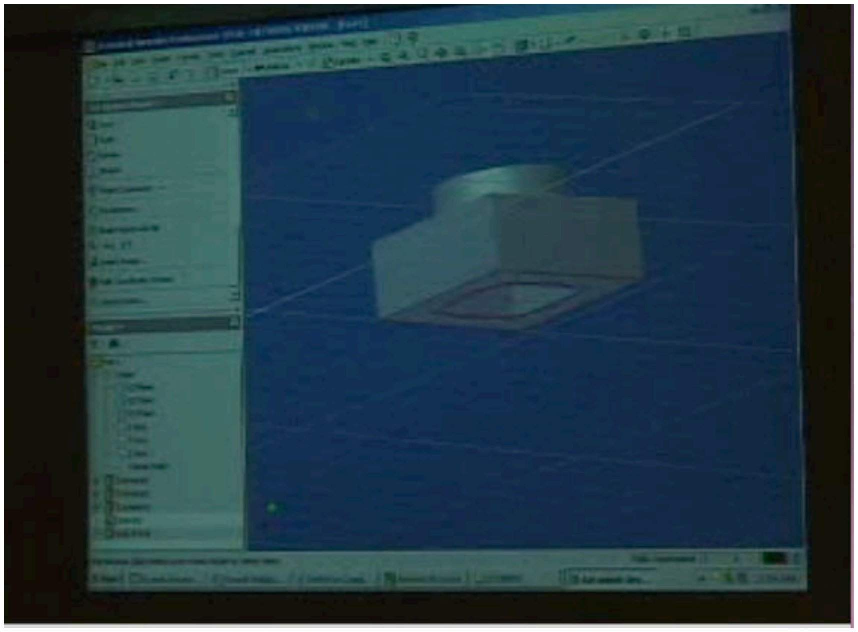

Figure 2: Still of video image from clip coded as not explicitly integrating the math concept of "geometric projection."

Excerpt 1: Embedded use of geometric projection

Teacher: I'm gonna project my geometry ["Project Geometry" is a software-specific command]...somewhere [Teacher searches through menu for command].

Students (several speaking the same time): (indecipherable) all the way at the bottom [of the menu].

T: I am at the bottom.

S: And then you go up (indecipherable).

S: It's not there.

S: Sketch [A "sketch" is a software-specific term for a type of user markup that can be referenced by the software but doesn't directly represent any real physical aspect of the piece being modeled].

Ss (several speaking the same time): (indecipherable)

T: Ahh, thank you. Let me put a sketch on there [adds sketch]. Now let me project my geometry of that circle. Where is it? There it is [locates circle]. I cannot project geometry of a center point. I have to project geometry of a circle and then from there I can go and see that center point. And did that put that sketch in the wrong spot? Yes. My sketch is actually on the bottom [of the Lego piece]. It shouldn't be.

S: It's too big for the (indecipherable).

T: Delete.

S: That was dumb (indecipherable).

T: It should...be put inside here [inside the hollow part of the Lego piece].

S: Oh.

24 S: But your circle's too big (indecipherable) [to fit inside the hollow area of the
25 Lego piece].
26 T: No it's not.
27 S: That's, that's okay that circle (indecipherable).
28 T (speaking the same time as the student): Cuz what I'm gonna do is project my
29 geometry of that circle. And again I'm gonna look at this first. And that
30 circle's bigger than my inside hole but that's okay. Cuz I'm gonna make a
31 smaller one. [The “nub” of the Lego piece is defined by an inside diameter
32 and an outside diameter, and there seems to be confusion about which circle’s
33 diameter is being referred to at a given time.]
34 S: Off the center point? [Teacher then continues on to perform an extrusion
35 operation.]

Notice first that from a mathematical perspective “projecting geometry” is probably ill-specified, or at least under-specified. Indeed, we see that in fact it is particular geometric *features* of the sketched circle that will be projected from one surface to another (Lines 13-18, 22-23, 28-35,), which is a good indication that the instructor is talking about the “Project Geometry” feature of this software and not, explicitly, the underlying mathematical idea of projection.

We see further evidence for this conclusion when the instructor notes (Lines 14-15) that “I cannot project geometry of a center point.” His point is not a mathematical one (and indeed there is nothing mathematically preventing one from projecting the center point of a circle on one surface to another), but that this software functionality does not support projecting a center point of a circle. In practice, one has to project the entire circle object and, as part of the software representation of the circle, the center point will be projected as well. This is an instance where, though there is an important math concept *present*, it’s not being taught *as* a math concept. In a way, the concept is “skillified” into the correct software specific procedures of navigating the proper menus, selecting the right operation, and constructing appropriate sketches. Consequently, much of the lesson addresses the idiosyncrasies of AutoDesk and its functionality, rather than the mathematical concept of geometric projection, which remains completely implicit here.

In contrast, we now look at a clip where we see both from the instructors’ and students’ verbal cues that mathematics, *as* mathematics, is brought to the fore of the class discussion. This clip comes from a small-group tutorial session later in the lesson of the same day. The students are measuring and making notes/sketches on the dimensions of the parts of various Lego devices that make up small robotic vehicles that they will later model component-by-component in the AutoDesk CAD environment.

Figure 3: Still of video image from clip coded as explicitly integrating the math concept "Reference Lines/Points/Planes."

Excerpt 2: Making geometry explicit in a measuring activity

1 Teacher (to Student 2): Explain to [Student 1] how you're gettin' all those things
2 [measurements of angles and distances] here by makin' points, for this one that
3 he's got there [points to S1's object and sketch].
4 T (to S1): Cuz you're gonna wanna do the same thing.
5 S1: What?
6 T: Find [i.e., specify the location of] a lot of points. Like [for] the angle here, you
7 wanna know where this point is here, or this point is here [points to object or
8 sketch the student is working with], from the top view, and then you know what
9 that angle is.
10 S1: Basically doin' a lot of geometry?
11 T: Yeah.
12 S1: [Mild expletive].
13 Ss: (laughter)
14 S2: You don't know geometry at all do you?
15 T: [Sarcastically] It's horrible when you have to use that math class stuff isn't it?
16 S1: I love math--I hate measuring shapes.

In the context of this exchange, it is clear that "geometry" (Line 10) refers to the mathematical discipline and the related mathematical objects and operations involved in linear and angular measures, rather than a feature of the CAD software's data structures. It is the student (S1) in this interaction that makes the explicit connection to a body of mathematical knowledge. S1's comment identifying the work they are doing (Lines 1-3, 6-9) as "geometry" (Line 10) may serve as a way to verify the student's hypothesis that this activity draws from that particular area of mathematics. This frames the work specifically to planar geometry and allows both the first and second student, as well as others who are apparently listening in (e.g., Line 13), to make this connection as well. This may help students to access relevant information to guide this activity, such as exploiting special angular values such as 90 and 180 degrees. It is also interesting to note that, in making a connection between the technical work and the mathematical body of knowledge, S1 also makes an explicit distinction between doing math ("I love math,") and some of the technical work involved in this task ("measuring shapes;" Line 17).

Table 7 gives the frequency that incidences of any math concept from the NCTM Content Standards were identified during the lessons we observed, along with the percentage of occurrences that those concepts that were identified were explicitly integrated. Less than a third of the occurrences of conceptual mathematics material were integrated explicitly by our criteria. Often, those that were explicitly made were among the earliest math ideas (such as referencing parts of geometric objects, or number operations), while the more advanced ideas (e.g., projective geometry and set theory) remained as embedded concepts within the taught procedures and software operations.

In light of the claims made by various stakeholders that *PLTW* courses—and pre-engineering courses more generally--bolster academic instruction in mathematics and the sciences, these data point to an important area of attention for those working to improve engineering preparation at the secondary level.

Table 7: Explicit integration of math concepts

Group	Concept	Number of incidences a Math Concept was Identified	% an Identified Concept was Explicitly integrated
Math Concepts: Geometry	Curvilinear Surfaces	3	33.3%
	Projection	7	0.0%
	Reference Planes/Lines/Points	7	42.3%
Math Concepts: Measurement	Measurement	7	28.6%
Math Concepts: Number	Number	9	44.4%
	Intersection (Set Theory)	1	0.0%
Total		34	29.4%

Discussion

The central objectives of this paper were to explore the extent to which integration of mathematics concepts with engineering is evident during classroom learning and instruction, and to characterize the nature of instruction. We presented a descriptive study of classroom learning and instruction as it unfolded across four lessons in *Project Lead the Way*'s *Introduction to Engineering Design* course, often the first of the 3 foundations courses taken by high school students. Earlier analyses of pre-engineering curricula suggests that despite the cognitive importance of focusing on concepts over skills and integrating those concepts to students' prior educational experiences, these events are rare in the student course materials and teacher training materials that make up the intended curriculum[24,25]. In light of these findings, we set out to investigate the occasions when concepts are introduced and document their explicit integration of during classroom learning and instruction.

Our findings, obtained from detailed analyses of videotapes of four classroom lessons, reveal, first, that more of the instructor's time was spent on (non-instructional) class management tasks, especially collecting and grading team project work, than on conveying scientific or technical ideas to students through lecturing and tutoring. Second, a greater proportion of the total observed instruction time was devoted to skills than concepts. Certainly, both skills and concepts are important to engineering education and practice[8]. Concepts do occupy a special place in that they play a more central role in organizing and applying knowledge, determining problem difficulty[12], and facilitating transfer. However, when we distinguish between engineering and math instruction, we see an interesting interaction, where skills were emphasized over concepts during engineering instruction, but concepts were emphasized over skills during math instruction (with science instruction absent during these lessons). This illustrates that engineering instruction was generally procedural whereas mathematics instruction (a smaller percentage of the lessons overall) was more likely to emphasize conceptual aspects. We also found that skills quite often presented without associated concepts, though concepts were most often presented in association with skills. Third, of those math concepts that were identified in the lessons, we found that only a small fraction of instruction was dedicated to explicitly linking these concepts to the engineering activities or operations used in class.

The US is actively striving to make engineering education more impactful and appealing to a broader range of young students. K-12 engineering education faces great challenges in advancing students' STEM knowledge and promoting the deep and well-integrated concepts and skills that can lead to the successful transfer of that knowledge. Yet such transfer is needed to address the novel challenges that the next generation of engineers will face[35]. This empirical research, while limited in scope because of the heavy demands of video data analysis, stands to identify where engineering education is poised to overcome these challenges, and where improvements can be made. Future research will be needed to replicate these patterns in more classrooms and across more courses and school sites. However, these results do corroborate other research of pre-engineering learning and teaching.[24,25,27] On that basis, these initial findings lead us to suggest that K-12 engineering course designers, instructors, and teacher educators look more closely at the embedded math and science within pre-engineering classes[8], and strive to make direct connections between the engineering activities and the broader concepts in order that they may tie new engineering instruction to students' prior knowledge, and to create a more effective educational climate for fostering conceptual understanding and transfer.

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