CHAPTER N

Academic Connections in Pre-College Engineering Contexts: The Intended and Enacted Curricula of Project Lead the Way™ and Beyond  
  
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Introduction

The current educational policy context demands that we define an integrated STEM education pathway that encourages a deep understanding of both technical and academic knowledge. Examples of these policies include the Carl Perkins Act, reauthorized in 2006, which mandates that schools integrate academic and technical education toward this end; the 2007 America COMPETES Act, which aims to improve the competitiveness of United States through investment in educating future STEM professionals; and most recently, Race to the Top funding, which encourages schools to adopt practices that prepare students to succeed in both college and the workplace. Further, publications coming from agencies such as the National Academies (ex. *Rising above the Gathering Storm,* 2008; *Engineering in K-12 Education*, 2009) call for educational leadership that optimizes knowledge-based resources to expand the number of students on the STEM career track as well as education research that directly studies the teaching and learning in pre-college engineering classrooms. Data on how American students compare to students in other developed countries in Science and Mathematics show that there is room for improvement in these areas. For example, 2009 Program for International Student Assessment (PISA) data shows that 15 year-olds in the United States scored lower than the Organization for Economic Cooperation and Development (OECD) average by 9 points, behind 17 other developed nations (out of 29) in mathematics literacy measures. While this data is an improvement over the 2006 data, where the U.S. ranked 22nd (OECD, 2007), it is no different from 2003 data. However, the United States achievement in scientific literacy is on par with the OECD average, behind just 12 other OECD countries. This, too, is an improvement over the 2006 data where the U.S. fell to 19th (OECD, 2007; Fleischman et al., 2010). The PISA data includes information gathered on a series of international assessments given to 15 year-old students to gauge reading, mathematics and scientific literacy. These assessments also include measures of cross-curricular skills and competencies. The emphasis is on functional skills that students have acquired throughout their schooling, making them particularly relevant for gauging preparedness of students to take on STEM subject matter. In this chapter, we will explore ways in which we can assess the teaching and learning in pre-college engineering classrooms relevant to the development of these cross-curricular skills and competencies.

What have recently been termed “mainline goals” for high school students contribute to the case for studying pre-college engineering. These mainline goals include helping students excel academically in science and math, increasing the number of high school students who go on to complete some level of post-secondary education and increasing technological literacy overall (Katehi, Pearson, & Feder, 2009). The use of Career and Technical Education (CTE) courses to achieve mainline goals is one way in which students can engage in class work that prepares them academically using project-based and problem-based activities, and we consider pre-college engineering courses to fall within this category. Kazis (2005) notes that vocational concentrators have lower dropout rates than students in either the general or academic high school tracks, indicating that these students are more productively engaged in school. In post-secondary education, among students who enroll within two years of graduating from high school, the percentage who persisted (either remained enrolled or completed a credential) was 87.2% for Engineering Technology concentrators (Bersudskaya and Chen, 2011). Career and technical education contribute a valuable linkage between the academic rigor and the applicability to the outside world – concrete connections are formed and students see relevance to what they are learning. The hands-on nature of career and vocational education appeals to students with varied learning styles, and encourages multi-dimensional learning and skill development. Recent longitudinal data from the National Center for Education Statistics (NCES) shows that 33% of the Class of 2004 completed 2 credits of CTE coursework and 16.6% completed 3 credits. Looking at post-secondary educational course taking, among the 2004 graduates who enrolled in post-secondary education and who had a post-secondary field of study related to their CTE concentration in high school, 1/3 of 2-credit CTE concentrators choose a major in STEM fields, but only 1 in 10 engineering technology concentrators choose an engineering college major (Bersudskaya and Chen, 2011) indicating that more can be done to encourage students to choose engineering majors.

CTE is less school-to-work preparation and more school-to-college-to-work preparation. 25% of all high school students are enrolled in CTE courses and of those students, 80% take the same number of science and math courses as non-CTE students. Further, they graduate with equivalent test scores (Gray, 2004). This data shows an improvement in trends reported by Levesque et al. (2000), who reported that CTE concentrators in the technology sector were taking fewer academic courses than non-concentrators. These findings lead us to conclude that CTE has a valuable place in helping students fulfill both mainline and “pipeline” goals – those related to filling careers in the STEM fields. Overall growth of jobs in STEM fields is projected to grow four times faster than the overall job rate; there is concern that there are comparatively too few graduates prepared to fill these jobs. Therefore, the aim of pre-college engineering should not only be to serve the academic “elite”, but all students who may have an interest in STEM careers and who might be able to use these courses to add relevance to the academic coursework, thereby allowing them to stay engaged with the coursework. In short, “CTE is to some students what honors curriculum is to others (Gray, 2004 p. 134)”. The trend of explicitly combining academic subject matter with vocational education has become increasingly common. The coupling of core academics with project-based curricula allows students to build a strong foundation of skills and work competencies along with knowledge of subject matter, opening up many options to every student upon graduation from high school (Plank, 2001). The core basis for PLTW and CTE overall is that students must engage in hands-on learning in order to make concrete connections between the skills and knowledge needed for high technology engineering careers. More than just achieving “mainline” and “pipeline” goals, students must understand that the skills and knowledge they learn today will be applied to problems; challenges facing the world as we move through the 21st Century. While preparing to be an engineer is one way to look at pre-college engineering, preparing to solve important problems is another equally important way.

Understanding how to assess teaching and learning in the pre-college engineering classroom will allow us to frame studies of these classrooms within the education and learning sciences in order to improve teaching and learning in this field. The hypothesized benefits of pre-college engineering course-taking are based on the particular curricula and how they are used. Specifically, what is the nature of the integration of academic material within the pre-college engineering course? Current research findings shed light on how pre-college engineering curricula are used in the classroom and how improvements can be made.

ENGINEERING IN THE PRE-COLLEGE CLASSROOM

CURRENT RESEARCH FINDINGS

Though scholars may attempt to provide normative accounts of what engineering education *should be*, our challenge is to describe what “engineering” is at the pre-college level by providing an empirical account of the nature of engineering education in the classroom. Much of what we know about this topic comes from observations of the enacted curriculum, and studies of the intended curriculum. In addition to describing the engineering education experience, it is also important to document how mathematics and science, which are central to engineering, are incorporated into the engineering curriculum. On a related note, we are faced with conflicting purposes for offering pre-college engineering courses at the high school level. Is the focus on providing educational opportunities for the advanced technological elite, or are efforts being made to include under-represented students to provide scientific literacy for all? Findings from recent studies of Project Lead The Way (PLTW) curricula shed light on how differences amongst teachers mirror these tensions. Further, the explicitness of mathematics integration with engineering is more common in advanced pre-college engineering classes. Explicit integration is important for knowledge transfer and is required if students are to apply their classroom learning to novel contexts. Thus, it is important that all students experience well integrated learning. Research findings on the current status of pre-college engineering curricula range from descriptive program overviews to studies of intended, assessed and enacted curricula in intricate detail These detailed studies of PLTW allow us to report how class time is devoted to concepts and skills in engineering, math and science, and to provide trends across the three foundations courses. In addition, a look at teacher training materials and how professional development affects teacher beliefs adds to our knowledge of where we currently stand with regards to the content, instruction and purposes of pre-college engineering curricula.

*Review of Teacher Beliefs Research*

Teachers as agents of instruction and enactment of principles and policies serve a unique and critical role in engineering education. One of the factors that shape teacher’s classroom practices is the knowledge, beliefs and expectations teachers have for their students, and how those beliefs may frame teachers’ perceptions of the purposes of these learning experiences. For example, Benner and Mistry (2007) found that higher levels of expectation from science teachers were positively and directly associated with student expectations, academic performance, and post-secondary academic attainment. Level of support from teachers and parents regarding math instruction is associated with students’ beliefs about mathematics, achievement goals, and efforts directed at learning mathematics (Chouinard, Karsenti, & Roy, 2007).

A report from the National Academy of Engineering (Custer & Daugherty, 2009) argues that teachers’ views have serious implications for the perceived place and purpose of engineering in the K–12 curriculum. Several recent studies have delved into STEM teachers’ views regarding K-12 engineering education. Yasar and colleagues (Yasar, Baker, Robinson-Kurpius, Krause, & Roberts, 2006) used a survey instruction to measure K–12 teachers' knowledge and perceptions of engineers and engineering practice, with emphasis on assessing teachers’ familiarity and views of the importance of design, and their perceptions of engineers and engineering practices. They learned that all of the teachers in the sample were unfamiliar with design and engineering, had low confidence in their ability to teach it, yet also subscribed to the value of integrating engineering into the K-12 curriculum and recognized its importance for preparing their students for later careers. In a separate study, Cunningham (2009) showed that that curriculum plays a powerful role in shaping engineering instruction for teachers, by helping them reflect on what they teach, how they teach, and who is likely to succeed in learning engineering.

While the role of the teacher and teacher beliefs and perceptions influence the engineering learning experience, there is little empirical evidence to adequately describe what has been identified as the “engineering teaching culture” (Steering Committee of the National Engineering Education Research Colloquies, 2006). In order to measure teachers’ views on pre-college engineering education, preparation for future studies in engineering, and expectations for success in engineering careers, Nathan and colleagues (Nathan, Tran, Atwood, Prevost & Phelps, 2010; Nathan, Atwood, Prevost, Tran & Phelps, 2011) developed the Engineering Education Beliefs and Expectations Instrument for Teachers (EEBEI-T; pronounced “eebee tee”). The EEBEI-T was originally given to 143 high school STEM teachers located in a moderately large urban city in the Midwestern US. Part one of the instrument includes a set of Likert scale items with seven reliable constructs (α ≥ .70). Reliability of the constructs was replicated with a second administration to a national sample of STEM teachers (N = 82).

Most teachers who completed the survey reported using students’ interests, prior academic performance, and cultural and family backgrounds to guide their teaching practices. Most teachers agreed that engineering learning takes place in multiple contexts, in and out of school. Yet a minority of teachers reported that they adequately integrate engineering activities and concepts into their courses. Teachers generally believed that to become an engineer a student must show high academic achievement in their math, science and technology courses. In contrast, student socio-economic status was not reported as an important consideration.

In addition to these patterns among all teachers, the EEBIE-T to be sensitive to group differences between those teachers who taught engineering education within career and technical education programs and those STEM teachers focused primarily on college preparatory math and science. As a group, math and science teachers saw engineering as rooted in high performance in math, science and technology. Engineering teachers, collectively, were far more likely to contend that their instruction effectively integrates engineering with math and science.

In the second part of the instrument, teachers read vignettes of four fictional high school students who had different academic, gender and socio-economic descriptions. The profiles were designed to compare in a more situated and more tacit way the impact of high versus low SES and academic performance on teachers’ views. The vignette data revealed that teachers tended to support enrollment in engineering classes and predict higher rates of career success for students from more economically privileged family circumstances, though it appears that teachers are not consciously aware of these influences.

Recently, the EEBEI-T was administered to high school STEM teachers in the summer and then again during the following winter in order to measure the impact on ones reported beliefs due to participating in the PLTW teacher professional development program and teaching the first semester of a PLTW course. Over time, teachers in the control group increased their level of endorsement for engineering classes, while those who actually went on to teach PLTW decreased their overall support. One interpretation is that nascent PLTW teachers formed a more realistic understanding of the demands of the PLTW program than their counterparts.

In findings highly relevant to the current chapter, newly minted PLTW teachers were more likely than a control group of non-PLTW STEM teachers to increase their reporting that STEM concepts were being effectively integrated in their classes (c.f. Cunningham, 2009). Given the importance of establishing an integrative view of engineering with science and mathematics (Moore, Roehrig, Lesh & Guzey, 2010; National Research Council, 2007; Schunn, 2009)

*Analysis of the Intended Curriculum*

Curricula – specifically, the text books, the worksheets, handouts, activities and materials that make up the course are critical materials to examine when looking for connections between instruction and learning. It is important to analyze intended curricula because they embody instructional views of what’s important by what’s covered and what’s not covered. Secondly, instructors internalize the views offered in the textbook even if they conflict with basic principals of educational reform that they might otherwise believe in – thus, the curriculum directly shapes the views of instructors and likewise, directly shapes the learning experience of students (Nathan et al., 2000; Nathan et al., 2002). After examining many pre-college engineering curricula from a broad viewpoint, Welty (2009) likened the model used in most curricula as “beads and threads” - the bead represents how projects and problems are framed or packaged, including what technologies are used to introduce students to engineering skills and concepts. Examples include how cell phones work, how special effects are created in movies or even something simple like the creation of Rube Goldberg devices. The threads in this model include the core concepts that run through the beads; engineering design, technology, science and mathematics.

Similarly, Nathan et al. (2008) took the foundations courses of one pre-college engineering curriculum in particular – Project Lead the Way (PLTW) and examined it in great detail to determine how well the mathematics standards were represented in both academic mathematics courses and the PTLW foundations courses. The mathematics standards used were determined by the National Council of Teachers of Mathematics (NCTM) and encompassed both *content* (including the topics of math; numbers and operations, patterns, functions, and algebra) and *process* (how math is performed and knowledge is created and verified; methods of data analysis, problem solving, reasoning, communication and connections across fields) standards for grades 9-12. The three PLTW foundations courses include Introduction to Engineering Design (IED), Principles of Engineering (POE) and Digital Electronics (DE). These three courses are the building blocks for the PLTW program and are generally taken in the order given. PLTW has been adopted by over 2700 schools (Katehi, Pearson and Feder, 2009) and is present in all 50 United States. This study examined the structure of both PLTW and mathematics curricula in grades 9-12. Both the mathematics and PLTW were similarly structured; each was composed of units, which contained lessons and activities, which allowed us to compare them to each other with regards to standards met at each level.

The following topics were covered in the PLTW courses:

*Introduction to Engineering Design* consists of the following topics: (a) history of design and; (b) introduction to design; (c) student portfolio development; (d) sketching and visualization; (e) geometric relationships; (f) modeling; (g) assembly modeling; (h) modeling analysis and verification; (i) model documentation; (j) presentation; (k) production; and (l) and marketing.

*Principles of Engineering*: (a) definition and types of engineering; (b) communication and documentation; (c) design process; (d) engineering systems; (e) statics and strength of materials; (f) materials testing in engineering; (g) reliability in engineering; and (h) introduction to dynamics/ kinematics.

*Digital Electronics* is intended to address the following topics: (a) fundamental principles of engineering; (b) number systems; (c) logic gates; (d) Boolean Algebra; (e) combinational circuit design; (f) binary addition; (g) flip-flop circuits; (h) shift registers and counters; (i) logic families and specifications; (j) microprocessors; and (k) student directed study topic such as design paradigm.

The question then was how was mathematics used in presenting these materials? What NCTM standards were being met by the PLTW curriculum? The mathematics text books, which were used as a comparison, were chosen because they were used by educators in our larger engineering education research project. These text books represented the academic mathematics curriculum and included standard books such as Glencoe’s Algebra, Geometry; Core-Plus Mathematics Project (CPMP) Courses 1-4 in Algebra, Geometry and Trigonometry, Prentice Hall’s Focus on Algebra, among others (Nathan et al., 2008).

Findings of this study indicate that while the academic curricula did emphasize *most* of the NCTM content and process standards, they generally lacked emphasis on measurement and work with data and probability, which are two areas best suited for integration with the pre-college engineering curriculum. Since only algebra, geometry and trigonometry texts were reviewed, it is possible that these standards are met in other math courses. However, the analysis of the PLTW courses intended curricula revealed very few points of integration across any of the three foundations courses, leading to the conclusion that mathematics is present, but weakly so (Nathan et al., 2008).

A second study of the PLTW foundations courses’ intended curricula (as well as the assessed curricula and teacher training materials) looked for explicit connections between mathematics and engineering concepts and skills in order better characterize the mathematics contained within (Prevost et al., 2009). While the original study conducted by Nathan et al. (2008) looked at absolute and relative frequencies, this study aimed to identify the occasions on which math and engineering were presented in an explicitly integrated way– given the evidence by research in the Learning Sciences that explicit connections are important for knowledge transfer, academic achievement and career readiness (Bransford and Schwartz, 1999). Explicit connection is defined as a specific point made with a mathematics principle, law or formula using mathematics vocabulary that depicts or demonstrates an engineering concept, task, skill or idea (Prevost et al., 2009).

Findings from this study focused on three main areas: 1) What emphasis was placed on explicitly integrating students’ conceptual understanding of mathematics and engineering topics? 2) What changes are observed over the three-course sequence? 3) How well aligned are the intended and assessed curricula? Content analysis was performed on the student materials in the intended curriculum as well as the assessments included in these materials. In addition, teacher training materials from the 2-week mandatory teacher training program were analyzed – yielding a more complete picture of how the curriculum can be used in the classroom. The analysis addressed dimensions of a) Clarity, comprehensiveness, accuracy and depth of mathematical inquiry and reasoning, organization and perspective, b) Engagement and timeliness, and c) Pedagogy, resources and professional development materials (Confrey & Stohl, 2004). The mathematics standards used for this study were again the NCTM standards for grades 9-12 and included both content and process standards. In order to understand the relative emphasis of the standards within each course over time, and within each portion of the course (ex. teacher training materials, assessments, activities, etc.) the percentage of each standard within a given unit was calculated by dividing the frequency of each standard by the total number of possible occurrences addressed within that unit. Overall, findings indicate that the explicit integration of math concepts and skills with engineering concepts and skills (as identified via scholarly publications, professional societies and popular accounts) was again apparent, but weakly so. Over the sequence of the three foundations courses, it appeared that IED was the least well integrated, POE was somewhat better and DE was the best in terms of integrating mathematics and engineering. While it makes sense that an introductory course would not cover much detail in either engineering or mathematics, this could be problematic for students who are enrolled in the PTLW sequence and have low math achievement, since they may only take one pre-college engineering course (Tran & Nathan, 2010). The project and problem –based approaches to learning engineering presented in the PLTW foundations courses are a good start, but the low integration of the academic mathematics with the engineering work could be improved by taking advantage of implicit opportunities and making them explicit (Prevost et al., 2010). The lack of explicit integration inhibits learners’ formation of broader generalization and abstraction of technical knowledge and does not allow learners to ground their understanding in concrete examples. These findings are consistent with findings elsewhere (ex. Welty, Katehi and Pearson, 2008). Further, Stone et al. (2008) found that when mathematics concepts were used in CTE courses such as the PLTW foundations courses, students did better on standardized math tests for both traditional math assessment and college placement, making a clear case for ensuring that explicit integration occurs within these curricula.

Two examples illustrate how a lesson could be shifted from implicitly to explicitly integrated. Implicit integration are areas where both math and engineering are used, but the definition of explicit integration is not met. In addition, they also illustrate the type of information that can be obtained in curricular studies of this nature. First, in Lesson 2.3 of POE (2004), students study how data can be presented. In this lesson, algebra standards could be explicitly integrated by having students graph functions as well as data sets. Students could compare the graphs of differentfunctions to those of the given data sets, thereby integrating additional Algebra standards. Then,they could see how their own modeling ability compares to thesoftware algorithm for finding a line of best fit (by using a trend-line in Excel™, for example). The mathematics embedded in Excel™ could be explicitly identifiedand connected with students’ prior work, and from there it could be reused in laterlessons. As a second example, in Lesson 4 of the POE (2004) curriculum, a slide presentation on sprockets and gears uses ratios to explain mechanical advantage. The math lessons in this presentation are well developed but are not made clear to the novice learner. For example, oneslide derives equations for the gear ratio, but the term’s definition is elusive and the ideas ofrelationships between variables (direct, indirect) are missed. Torque, a central concept, is notdefined. When these concepts are tested in activities, they have only equation-based questions,just as the abstract lessons have only abstract questions. The math is kept in the realm offormulas, so the connections between the mechanical principles and the math lesson are verylimited. Both Algebra and Geometry standards could be better integrated – for example the number of teeth ona gear is connected to circumference or arc length and this should be pointed out; explicit consideration of the concepts of linear and rotationalmotion would provide math content while elucidating the relationship between gears of differentsizes.

*Analysis of the Enacted Curriculum*

Taking the analysis of the course materials a step further, Nathan et al. (2009) and Prevost et al. (2010, 2011) looked at the enacted curriculum – that is, how did teachers in several high schools actually teach the PLTW foundations courses? Did the teachers explicitly integrate the math and engineering? In order to conduct these studies, researchers first recorded 14 hours of video in high school PLTW classrooms representing 14 class segments. These videos were digitized and entered into Transana (Fassnacht & Woods, 2005), a computer application that integrates video, transcript text and researcher codes to allow both qualitative and quantitative analysis in the classroom and other settings. Each classroom episode was divided into clips and clips were coded to reflect the points of interest related to the use of mathematics skills and concepts, engineering skills and concepts and the nature of the integration of these areas. Researchers coded the video for the occurrence of *concept,* which denote engagement with “big ideas” in engineering and mathematics (ex. “modularity”, “projection”, etc.) and *skills* or process-oriented tasks that may or may not require conceptual understanding but are important for completing engineering work. Concept codes in this study encompass the content codes from the NCTM math standards. Similarly, skill codes include the NCTM process standards. These codes, along with those used for coding the engineering work done in the classrooms are described in Table 1 and Table 2, below.

Table 1: Concept Codes

|  |  |
| --- | --- |
| Concept 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. |

Table 2: Skills 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. |

In addition to looking at the enacted curriculum itself, the authors also explored the nature of the instruction in the classroom, breaking down how the time was spent by the instructor with regards to interactions with students (instructing students, tutoring individuals, or on non-instructional tasks) and how students spent their time in class with regards to project work (working alone, in pairs, groups or with the instructor).

As with prior curricular analyses, these studies found that the amount of explicit integration of mathematics and engineering improved across the three foundations courses, with the most integrated course being the final foundations course DE, and the least being the first course, IED. The material in DE was found to be explicitly integrated 77.5% of the time, which is consistent with the nature of the material presented in DE – that is, the mathematics and engineering used in digital electronics is practically inseparable and is equally skills and concept based. The curriculum incorporates Karnaugh mapping, Boolean algebra (notation, transformation and theorems) and the creation of circuits using breadboards, among other things. In comparison, explicit integration is observed only 29.4% of the time in IED and 51.8% of the time in POE, showing a continuing trend of improvement as the PLTW foundations courses progress with regards to explicit integration that is consistent with earlier analyses of the curriculum. These numbers were determined by dividing the total amount of time included in clips coded as explicitly integrated by the total amount of time coded with at least one mathematics or engineering skill or concept.

To better illustrate what explicit integration is, specifically, Prevost et al. (2011) give an example of students who are wiring a digital alarm clock on a breadboard as the transcript appears in Transana. The circuit was designed in Multisims and the dialogue presented is discussion surrounding debugging of the circuit. In order to complete this project, students must understand the inputs and outputs (logic functions). In lines 2-5 and 6-9, the instructor directs the student to the diagram that was created in a prior assignment to compare what was figured on paper to what had been wired (by counting and integrating each circuit).

1 S: Where are the switches supposed to connect to?

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

5 S: One and two have to be together.

6 T: (at the same time) So you gotta hook one and two hook together.

7 And what do you do to that? Then you hook that, to the switch. Make sure your

8 ground is seven. Power is VCC. Count down, count up. ‘Kay. Then you got four

9 of ‘em. One two three four. Everything’s done off identical to that.

10 S: Okay

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

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

Further, these studies found that the amount of time the instructor spent directly working with students followed the established pattern. In DE, the teacher interacted with the students 96% of the time. Since the DE curriculum is so project heavy, much of this time (74%) was spent working with students one-on-one or with small groups. This level of attention given to students by the instructor is the highest of any of the foundations courses. In the earlier courses more time was taken out of the 40-50 minute period for non-instructional class management (60% for IED and 23% for POE). One can observe this as the nature of a project-based curriculum. In the introductory course, students cover several projects, devoting little time to each. In the later courses, more time is spend on each project so less time needs to be spent managing the class during set-up and getting started with each project (Prevost et al., 2011). However, with the goals of getting more students interested in engineering careers and helping students be able to perform at academic levels that would enable them to achieve these careers, a higher level of explicit integration is needed earlier in the curricular sequence.

IMPLICATONS

Lastly, the implications of the findings from our research surrounding the academic-technical connections in pre-college engineering contexts are examined. For practitioners – teachers using pre-college engineering curricula in their classrooms -- the findings suggest new approaches for how curricula are enacted and assessed in the classroom. For school leaders and district curriculum developers, the implications for explicitly integrating STEM subjects in and across classrooms, schools, and in community settings will require changes in professional development supports, as well as enhancements to extant organizational and professional cultures. For policy makers examining integrated STEM education initiatives, the implications for funding, performance accountability teacher credentials, and successful school-to-college transition are discussed broadly.

*Implications for Practice and Professional Development*

Research findings presented here offer insights and guidance for re-thinking the pedagogy of pre-college engineering education in middle and high schools. Acknowledging the significant gaps in our understanding of how K-12 students learn and could be taught engineering concepts and skills optimally (Katehi, Pearson, & Feder, 2009), we offer some general implications for improving practice and professional development using the framework for engineering education described at the outset of the chapter.

To address the challenges of ensuring that all students are both college and career ready (Provasnik et al., 2009), pre-engineering programs, academies, and/or courses must provide students with substantially re-designed learning environments. Effective learning opportunities are advanced when they are centered on students' interests and capacities, knowledge production, community connections, and assessment (Bransford and Schwartz, 1999). Pre-collegiate engineering learning must enable students and teachers to make deep and explicit connections between the content of engineering (design, principles, digital electronics, introduction to engineering specialties), requisite or essential academic knowledge (physical and chemical properties of materials, biological structures), and the contexts in which the technical and academic learning is applied to addressing societal challenges. By linking learning to broader frameworks and societal purposes, see the Grand Engineering Challenges (National Academy of Engineering, 2008), students from diverse backgrounds, including girls and students for poor families begin to understand how engineering and technology expertise is central to major societal problems, such as providing access to clean water, making solar energy economical, or restoring the U.S. urban infrastructure.

Turning to instructional practice, it is important to keep in mind the key lessons espoused by the National Academy's Committee on K-12 Engineering Education (Katehi, Pearson, & Feder, 2009). Building on the Committee's three lessons (pp. 140-143) and the AWAKEN studies, teachers and high school leaders should:

1. Allocate sufficient instructional time to develop core engineering concept understanding through immersion in extended design activities that explicitly connect engineering skills and concepts to mathematics standards.
2. Encourage iterative, purposeful revisions of student designs that embody current and realistic challenges facing engineers (ex. National Academy of Engineering’s Grand Challenges).
3. Sequence instruction to build from easiest to learn engineering core concepts to the challenging to learn concepts, all the while integrating academic subject matter. As shown, the PLTW foundations courses do follow this pattern. 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.
4. In many secondary school settings, new or expanded professional development practices are needed to advance the implementation of engineering education. Our studies of classroom instruction suggest that teachers often ignore or overlook opportunities in design, principles, and digital electronics classes to illustrate how core scientific and mathematical knowledge is fundamentally important to correct, accurate engineering solutions. The missed opportunity to make explicit connections is, fundamentally, a teacher professional development challenge. As the Committee on K-12 Engineering Education (Katehi, Pearson, & Feder, 2009) noted, many teachers are afraid of teaching science and engineering, thus teacher development initiatives must defuse the feelings of ineptitude through engagement (p. 112). The substantial differences between math and science teachers and Project Lead the Way teachers (mostly CTE instructors) is reflected in their significantly different beliefs about the importance of high academic performance in math and science for becoming an engineer. The EEBEI-T instrument can be used in schools to assess instructors' views, both before and following systematic professional development experiences, on the academic connections between math, science, and technical skills and knowledge for success in the engineering career pathway. As noted earlier, participation in the PLTW summer institutes and an initial semester of PLTW instruction did not raise the PLTW instructors' beliefs on the importance of academic achievement. Thus, new professional development models for culling out and teaching the explicit connections between core science and math content and technical or engineering principles and applications could be quite beneficial in advancing broader understanding and teacher knowledge about the centrality of engineering education.
5. Without question, the development of teacher professional knowledge and motivation is one of the key strategies for advancing pre-collegiate engineering education or Integrated STEM Education as envisioned by the National Academy Committee. However, when high quality instruction requires both recent content knowledge and pedagogical content knowledge in other related fields, wholly new school-level designs and innovations may need to be considered. The recent literature on STEM teaching suggests that some school districts and states are:
   1. Creating STEM leadership or instructional teams to develop and implement integrated courses or core themes. Often, the introduction of team-taught courses, such as Engineering and the Environment or Engineering and Energy Solutions, can stimulate broader curriculum innovation.
   2. Initiating STEM or Engineering-focused small learning communities, such as career academies, with planning and professional development funds available from various Federal programs administered by States, including Charter Schools, Perkins Career and Technical Education, or Math-Science Partnerships. Several regional and local foundations are supporting similar initiatives.
   3. Developing local and regional alliances with universities to develop dual credit arrangements in Engineering and related technology education departments. Project Lead the Way is the most prominent model for awarding college credit to high scoring students who complete end-of-course assessments in one of seven Engineering courses. High school PLTW instructors are trained and certified in two-week summer institute held at a state-affiliated Engineering college or university.

*Implications for Public Policy*

As noted in the introduction, the extended and challenging global recession, which began in 2008, has continued to stimulate calls from the private and public sectors for education policies and programs capable of providing a high-skilled, high-wage workforce. Reports from the National Academies, national commissions, and prominent professional associations, such as the National Governors Association, continue call for new strategic alignments of secondary and postsecondary education pathways in STEM, Engineering, and Health Sciences. Many of the recent reports offer an interesting interplay of public policy recommendations are likely to significantly influence the future design and implementation of engineering education in schools and beyond.

The Chicago Council on Global Affairs' *Master Plan for Higher Education in the Midwest* (Duderstadt, 2011) calls for:

* All higher education institutions must become significantly more engaged in partnerships with K-12 education to address the challenges of improving: teacher quality, pathways for all students across and between education levels, college completion rates, and peer-to-peer relationships among faculty members to strengthen STEM education.
* To prepare students for tomorrow's unknown challenges of careers and citizenship, universities must help students develop and *assess* the higher order intellectual skills necessary to cope with a future of con­tinual yet unpredictable change (e.g., critical thinking ability, a commitment to lifelong learning, the ability to adapt to change, and the capacity to thrive in a world of increasing diversity).

In addressing the role of education in the state's economic development strategies, the National Governor's Association (Sparks & Waits, 2011) has recommended that Governors:

* Set clear expectations for higher education's role in economic development.
* Encourage employers' input in higher education.

Engineering and applied sciences will be templates for other schools and colleges as they develop new programs and program enhancements (i.e., new certificates) in response to industry input and labor market demand data. Additionally, engineering programs at the university, community college, and high school level will provide more faculty and students with opportunities to systematically access and engage industry partners via internships, research opportunities, project-based learning assignments, and faculty externships.

Track higher educational institutions’ impact on students’

Despite limited evidence that these policies have an influence on teaching and learning outcomes in engineering education, these public policy changes are often viewed by policymakers as central to state or regional economic recovery or productivity. Whether viewed as a pipeline or mainline educational innovation, high quality engineering education holds much promise for enhancing both the public and private returns to education investments in the 21st century.

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