Adapting a Post-Secondary STEM Intellectual Model to K-5 Mathematics Instruction

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Abstract

If Science, Technology, Engineering, and Mathematics (STEM) education is to be improved, knowledge about teaching and learning for STEM disciplines should be a fundamental consideration in curriculum design. This study examines the efficacy of a mathematics project that adapts a post-secondary instructional model developed by Richard M. Felder and Elizabeth Brent to the lesson design of an elementary mathematics curriculum that includes materials for K-5 classrooms and for K-5 teacher development. The purpose of this paper is to describe how the Felder/Brent instructional model for post-secondary engineering students adapts to an elementary environment and supports mathematical development in elementary students and their teachers. Preliminary findings in student achievement on a statewide assessment will be presented, and plans for evaluating the relationship between program implementation and student achievement will be shared.

Introduction

Enabling students from the earliest grades to develop confidence and competence in mathematics prepares them for a competitive job market and makes higher education more accessible. Failure to advance in Science, Technology, Engineering, and Mathematics (STEM) “gate keeper” courses is by far the leading cause of low numbers of Americans who are prepared to enter technical jobs out of high school or to enter engineer/technical degree programs at universities in this country. Preparing students to enter the job market or degree programs with mathematical confidence and competence not only increases their own personal opportunities, but it also contributes to the advancement of a well-prepared and competent American citizenry. Consequently, STEM preparation at the earliest grades is not only a matter of personal equity, but also a matter of social responsibility.

Because the foundation for STEM careers is laid in elementary classrooms, a pre-engineering mathematics curriculum program is a long overdue consideration. A team of K-16 educators and elementary classroom teachers, under the guidance of faculty from the College of Engineering and Science at Clemson University are developing a K-5 mathematics curriculum program designed to students for STEM disciplines and to prepare teachers to teach these students. This curriculum is designed to provide elementary students with the kinds of learning experiences that will not only prepare them for higher level STEM courses, but will also provide them with an interactive learning environment where communication and collaboration skills are developed. Such collaborative working environments are essential to production in many of today’s STEM careers so if students expect to succeed in engineering and technical fields, preparation must begin in the early grades to ensure that students have the kinds of learning experiences that enable them to achieve this success.

Features of the Curriculum

The pre-engineering mathematics curriculum program described in this paper has been designed based on the premise that access to innovative learning tools and well prepared teachers is a matter of equity and social responsibility. In school districts across the nation, shortages of qualified teachers and diminished resources for professional development and instructional materials prevail, and nowhere more acutely than in the high poverty communities, where math achievement for students is at the lowest (Hirsch, 2002). In response to this disparity, the developers of this program have partnered with districts in culturally isolated, high poverty communities to provide the material and professional development resources needed to meet the challenge of preparing *all students* for STEM educational opportunities.

Instructional Materials—Research has shown that if children are to develop abstract concepts they must use their senses to investigate concrete representations of those concepts. Pictures in a book or concrete examples demonstrated by the teacher are not sufficient for students to develop meaningful understanding of complex ideas. They need to manipulate the materials and investigate the ideas in ways that help them to personally develop the concepts. All children, from every socio-economic class, are entitled to these kinds of experiences. The curriculum program described in this paper meets this challenge by including inquiry-based lessons and all the instructional materials needed to teach those lessons, so that in a class of 30 children, every single child will have the opportunity to explore how things fit together and come apart, how things are similar and different, and which ideas make sense and which do not. By including these instructional resources, this curriculum program incorporates "learning-by-doing" theories of cognition. Providing teachers with resources that support such theories, ensures that "abstract instruction and concrete illustrations" are combined so that students are engaged in cognitive processes that support both retention and transference of knowledge (Anderson, Reder, & Simon, 2000).

In addition to the materials designed for K-5 classrooms, this curriculum program also includes instructional resources that focus on teacher development. Research suggests that the single most significant factor in laying a solid mathematical foundation in the formative K-5 years is the elementary teacher. By focusing on the learning needs of both students and their teachers, this synergetic pre-engineering curriculum program enables teachers and students to develop confidence and competence in math. The teacher materials are designed based on the premise that teachers need to experience inquiry as a learner before they can support it as a teacher. Using the student materials as a basis for teacher development is a groundbreaking approach to teacher education that makes sense (Ball & Cohen, 1996; Collopy, 2003; Davis & Krajcik, 2005; Diaz, 2005; Harris, 2006; Lloyd, 2002; Remillard, 2000; Russell, 1997; Schneider & Krajcik, 2002; Spencer, Chiappinelli, & Mark, 2004; Reyes, Tarr, & Chavez, 2004). The student materials and tasks are adapted so that teachers can explore the mathematical ideas in ways that will help strengthen their understanding of the concepts and improve their ability to help children develop those concepts. *In short this curriculum program is developed so that teachers are provided the resources and training they need to create and support mathematical environments where diverse learners work together to develop mathematical confidence and competence.*

Instructional Model—This is an inquiry-based curriculum program designed to promote the development of STEM faculties and to provide learning opportunities for diverse groups of students. Recent studies in cognitive psychology have led to many of the currently held views of intelligence and cognitive learning styles that highlight ways to increase educational effectiveness in STEM disciplines by improving instructional methods (e.g., Anderson, Reder, & Simon, 2000; Baumgartner, Lee, Birden, & Flowers, 2003; Carver and Klahr, 2001; Doyle, Edison, & Pascarella, 2000; Grouws & Cebulla, 2000; MacRae-Campbell, 1989; Wolfe, 2001). Two of the foremost leaders in the study of the intellectual development of science and engineering students at the post-secondary level are Richard M. Felder and Rebecca Brent. Felder and Brent propose an instructional model that is designed to advance students in a "developmental progression" in which they take "increasing responsibility for their own learning" (2004, p. 279). Five components comprise this instructional model: 1) variety and choice of learning tasks; 2) explicit communication and explanation of expectations; 3) modeling, practice, and constructive feed-back on high level tasks; 4) a student-centered instructional environment; and 5) respect for students at all levels of development.

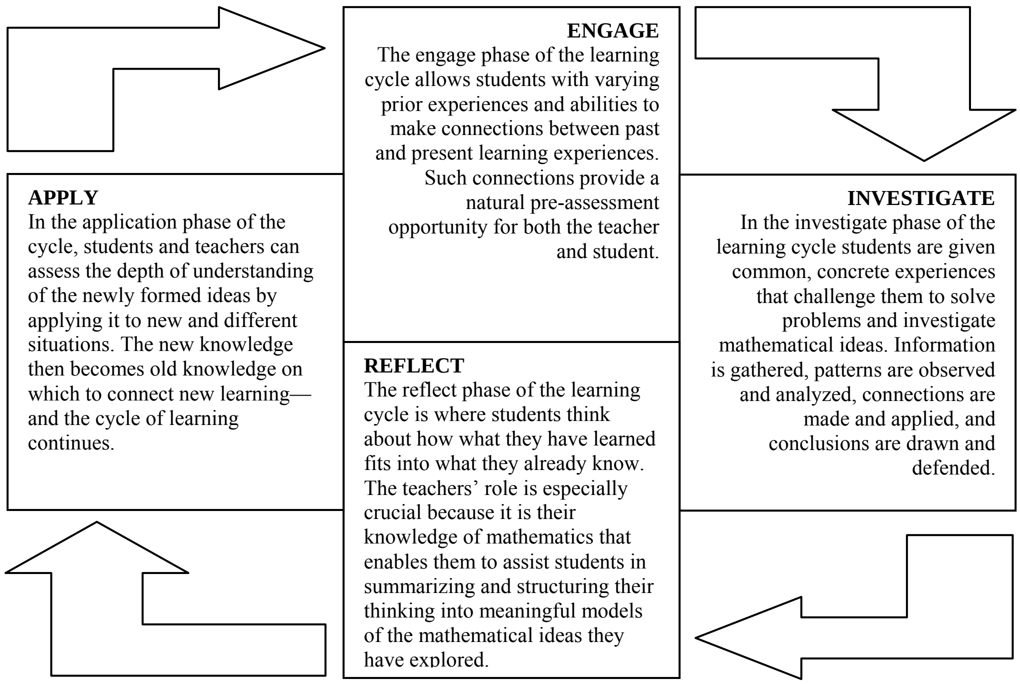
The instructional model recommended by Felder and Brent is based on the STAR Legacy learning cycle that was first conceived and developed through the NSF-funded VaNTH intitiative for engineering education at Vanderbilt University (Bransford, Brown, and Cocking, 2000; Brophy, 2000; Schwarz, Brophy, Lin, and Bransford, 1999; Schwartz, Lin, Brophy, and Bransford, 1999). The instructional approach supported by learning cycles like the STAR Legacy module is consistent with the principles of cognitive science and based on the *How People Learn* Framework (Bransford, Brown, Cocking, 2000) which consists of four elements:

i) Learner-centeredness: The class environment and instructional tasks take into account the knowledge, skills, preconceptions, and learning styles of learners.
ii) Knowledge-centeredness: Instructional tasks that help students learn with understanding by thinking qualitatively and by organizing their knowledge around key concepts.
iii) Assessment-centeredness: Frequent opportunities are provided for students to make their thinking visible in order to help them refine their understanding.
iv) Community-centeredness: Classroom norms are fostered that encourage students to learn from one another and that recognize the teacher as a co-learner.

Each lesson in the K-5 pre-engineering curriculum program is designed based on a four phase learning cycle *Engage-Investigate-Reflect* (Diagram A) that is similar to the five phase STAR Legacy learning cycle, *Challenge-Initial Thoughts-Perspectives/Resources-Assessment-Publish*, which is the basis of the Felder/Brent Instructional Model. See the Appendix for a detailed comparison of the STAR Legacy learning cycle and the pre-engineering learning cycle.

The structure of the K-5 learning cycle is such that the components recommended by Felder and Brent in their instructional model are embedded throughout each lesson. Throughout the learning cycle of each K-5 lesson, students are: 1) given variety and choice in learning tasks; 2) expected to communicate their thinking both verbally and in writing; 3) provided opportunities to model and practice with other students, with the expectation of constructive feed-back from peers and the teacher; 4) given tasks that are student-centered in nature; and 5) expected to work cooperatively in various group configurations to accomplish tasks. By developing this model of instruction from the earliest grades, a pipeline of educated, motivated students will complete the elementary grades better prepared to enter STEM disciplines.

Diagram A: The K-5 Pre-Engineering Learning Cycle



Communication and Collaboration—The need for collaboration and effective communication are essential to production in STEM related careers. Developing collaborative and communicative skills in the early grades helps prepare students for effective participation in the STEM fields.

Discussion, questioning, reflection, and writing are communication strategies that ensure that meaningful mathematical thinking occurs in classrooms and that effective collaborative skills are being developed. Communication in the mathematics classroom permits learning to build on the students' informal knowledge, gives students practice in explaining their mathematical thinking to others, and provides students and teachers with evidence that learning has occurred (Yackel , Cobb, Wood, and Merkel, 1990; Malloy, 1997; Moody, 2004). Such experiences are essential to creating a collaborative learning environment.

The communication model found in the lessons of this program provides a structure for successful verbal and written experiences throughout each lesson. This model results in a community in which students have the freedom to take risks so that verbal and written communication can occur and develop. In the lessons, communication evolves and improves as discussion and writing moves from part of a community to individual accountability. Conversations that "promote analysis, reflection, and critical thinking" and that "instruct and stimulate thinking might be particularly important for language minority students, many of whom receive insufficient opportunities for conceptual and linguistic development at school" (Goldenberg, 1991, p.1).

Lessons begin with whole-group communication where students and teachers brainstorm together to develop a representation or generalization of a mathematical concept. In the Engage phase of the Learning Cycle, the teacher can assess the prior learning of the student. Later in the Investigate phase, students work in collaborative groups permitting the mathematical thinking to evolve in the safe environment of collaboration. After each student writes to show his or her own mathematical thinking, another whole group discussion takes place in which ideas are shared, changes in thinking are discussed, and ownership of the learning takes place.

The communication model employed in the lessons is based on research that considers the reflection process to be essential to the learning process (Schon, 1983; Confrey, 1990; Moon, 1999). Schon described two types of reflection—reflection-in-action, which is known as "thinking on our feet," and reflection-on-action, which involves exploring why we think the way we do. The learning cycle model of instruction found in each lesson of the pre-engineering curriculum program provides a structure for continuous reflection-in-action as students represent, verbally communicate, and compare their findings throughout each lesson. The Reflect phase of the learning cycle provides an opportunity for focused reflection-on-action as students are asked to examine and explain their thinking by writing about what and how they have learned. It is through this linked process of reflection, in-action and on-action, that students take responsibility for and ownership of their learning, as recommended by Felder and Brent (2004).

Many leaders in mathematics education recognize that writing can play an integral role in helping students learn mathematics (e.g., Davidson & Pearce, 1988; King, 1982; Salem, 1982). For this reason, writing plays an integral role in the development of mathematical ideas in this curriculum program. Teachers model writing in a variety of contexts, including the creation of vocabulary wall charts relevant to the topic; documentation of student ideas from brainstorming sessions ; and writing displays that not only effectively summarize and organize the learned information from the lesson, but also provide an accurate model of well-written summaries of the learning. The expectation that students provide written records of the mathematical ideas they have developed is included in every lesson. This embedded expectation of writing to develop and demonstrate understanding is indicative of the STAR Legacy "publish" phase and of the modeling and practicing components of the Felder/Brent instructional model.

Another important consideration in the development of this curriculum program is the uniqueness of mathematical language and the special attention it requires as it is developed by children. Many sources indicate that success in mathematics is best accomplished through activities that use the language of mathematics as a tool for developing mathematical thinking (Brickmore-Brand, 1990; Baker & Baker, 1991; The Mathematical Association, 1990; Usiskin, 1996; Whitin & Whitin, 2000). Each lesson in this curriculum program supports the development of standard mathematical vocabulary, conventions, and representations. This is accomplished by providing opportunities for students to explore a mathematical concept through a variety of concrete experiences and by routinely encouraging students to communicate their understanding using mathematical language and conventions that are both accurate and developmentally appropriate. By including standard mathematical language and conventions throughout the curriculum program, STEM development is fostered and advanced, so that students are not only better prepared to study STEM subjects at higher grade levels, but are better prepared to communicate complex ideas in standard mathematical language, starting at the earliest grades.

Research shows that questions are an effective learning tool when teachers use effective questioning techniques (Anderson et al., 2001). Effective questioning helps students cement skills, explore concepts, and self-assess their own knowledge. Each lesson includes questions that are designed for different purposes and for different levels of thinking, so that students will connect present learning with past learning, share their ideas with each other, develop the ability to think critically, and be responsible for their own learning. A safe environment for asking and answering questions is essential to success in the mathematics classroom and this kind of environment is fostered through this mathematics program. Confident, secure teachers are comfortable with the fact that discussion is not going to be predictable and that they may not always know the answer (Bransford, Brown, and Cocking, 2000; Marzano, Pickering, and Pollack, 2001). This is explicitly communicated and modeled throughout the professional development component of this program.

By attending to the curriculum design to include instructional materials that provide opportunities for students to explore concepts, an instructional model that is based on post-secondary engineering education, and that supports the development of communication and collaborative skills, this pre-engineering curriculum program will lay a solid foundation for STEM development in elementary students.

Preliminary Results from South Carolina and New Jersey

South Carolina: Internal Evaluation—In 2004 four South Carolina schools field-tested the third grade algebra module *Plotting and Growing* during the second semester, prior to the administration of the statewide assessment PACT. The rationale for comparing the third grade students from the four schools in 2003 (prior to introducing this curriculum module) with the third grade students in 2004 (after introducing the curriculum module) is based on the similarities of educational expectations and opportunities within each of the four schools over the two year period. Though all four schools differed in terms of demographics, resources, instructional expectations, and educational opportunities, each of these areas remained somewhat constant for both groups of third grade students (2003 and 2004) *within each school*. While being distinct in terms of demographics, instructional expectations, and student populations, the demographics of the collective group of four schools were consistent with South Carolina demographics.

By grouping the tested students from the four schools into two sub-populations, Third Grade Students NOT USING the curriculum unit (2003) and Third Grade Students USING the curriculum unit (2004), reasonable comparisons were made between student subgroups. Using the statewide assessment scores as a basis for comparison (percentage of students meeting standard), PACT achievement levels for the 2003 and 2004 third graders in all four schools were compared to each other and also to third grade students statewide. See Table A for the comparisons among subgroups.

Table A: Third Grade Field Test Results on PACT*

Populations		Percentage of Students Meeting Standard on PACT: 2003 students NOT USING curriculum unit	**2004 students USING curriculum unit**
Third Grade Students	Four Schools	81.3% N=344	**87.3% N=316**
	Statewide	*82.3% N=48,833*	*82.7% N=48,378*
African American Students	Four Schools	69.0% N=155	**82.8% N=128**
	Statewide	*71.6% N=20,021*	*72.8% N=19,351*
White Students	Four Schools	91.2% N=172	**92.4% N=172**
	Statewide	*90.9% N=26,369*	*90.4% 26,124*
Full Pay Meal Plan	Four Schools	89.8% N=147	**94.2% N=137**
	Statewide	*91.8% N=22,463*	*91.1% N=22,253*
Subsidized Meal Plan	Four Schools	74.9% N=195	**81.7% N=180**
	Statewide	*74.6% N=26,369*	*75.7% N=26,124*

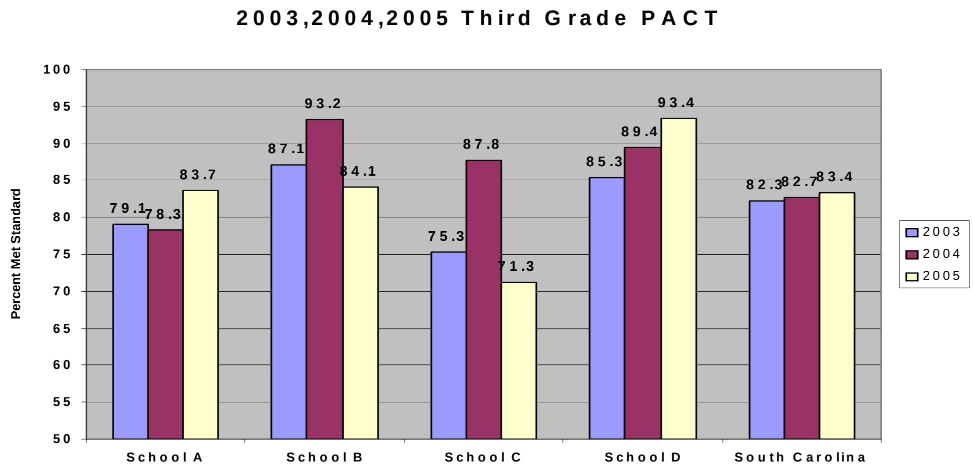
*PACT—Palmetto Achievement Challenge Test, South Carolina statewide assessment, aligned with NCTM mathematics standards, recognized as one of the best state accountability systems in the nation by the Princeton Review (2003).

When comparing the four-school population to the statewide 2003 population, prior to introducing *Plotting and Growing* in the four schools, the percentage of students statewide meeting standard were similar to the percentage of students in the four schools meeting standard. Not only were the collective demographics of the four schools similar to South Carolina, but levels of mathematical achievement were also similar in the 2003 school year. However, in 2004, after introducing *Plotting and Growing* in the four schools, the percentage of students meeting standard in the four participating schools *exceeded the statewide percentages for every subgroup*. Most strikingly, the math achievement of two student subgroups, African Americans and subsidized meal assistance recipients, was significantly improved. In meeting the challenge of closing achievement gaps for underrepresented subgroups of students, the significance in improvements in these two subgroups was especially noted.

In the 2004 field test, the curriculum module, *Plotting and Growing*, consisting of 20 lessons, was taught over a 7 week period, early in the second semester of each of the four schools. Improvement in mathematics achievement was immediate in three of the four schools. In the 2005 field test, a new Geometry module, *Shapes and Paths*, was implemented in two of the four schools. In those two schools, *Plotting and Growing* was taught during the first semester and *Shapes and Paths* during the second semester. For a variety of reasons, two of the schools chose not to participate in the 2005 Geometry field tests. District pacing guides, new teachers at the grade level, and other factors influenced the extent to which the previous year's Algebra module *Plotting and Growing* continued to be used in 2005 in the two schools that did not participate in field testing the Geometry module. New teachers in the two non-participating schools did not use the materials at all, and returning teachers reported using the materials sporadically rather than consistently as they were designed to be used.

Of the two schools that continued to participate in the 2005 Geometry field test, using both the Algebra and Geometry modules, the percentage of students meeting standard in both schools improved. For the two schools that did not continue to participate in the 2005 field test, where inconsistent or no implementation of the Algebra module was documented, the percentage of students meeting standard in 2005 fell below the 2003 levels. See Table B for the longitudinal display from 2003 to 2005 in each of the four schools below. Also included in the graph is the statewide longitudinal information for comparison.

Table B: Longitudinal Display 2003-2005

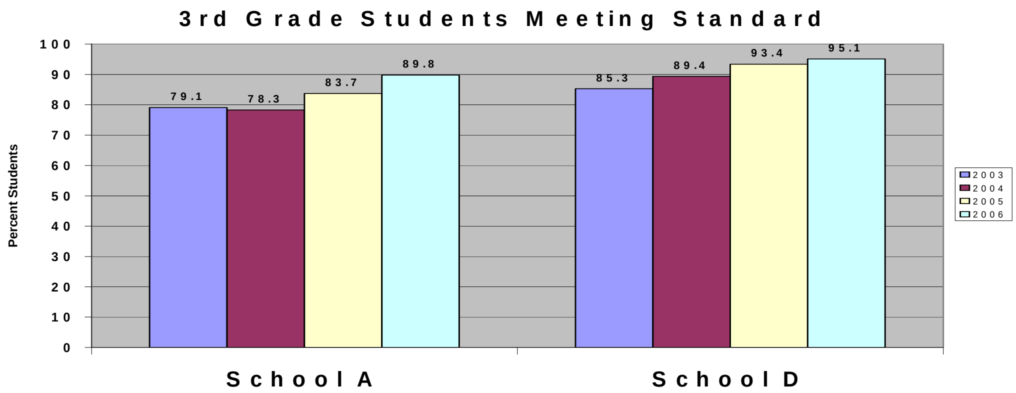


Schools A, B, C, and D all field tested the Algebra module in 2004.
Schools A and D continued to implement Algebra module and field tested Geometry in 2005.

These results, while preliminary and not conclusive, do show *immediate improvement* in three of the four schools during 2004 when all four schools participated in the field test. Conversely, student math scores *immediately declined* in the two schools that discontinued participation in the field test and implementation. Such immediate outcomes, however preliminary, suggests that this program can potentially impact mathematical achievement among students from diverse environments, with diverse groups of teachers.

Schools A and D continue to participate in the field test of new units and to implement the published strands. They have continued to show improvement on the statewide PACT assessment. Both schools are designated as Title One schools because of the poverty index of the students who attend the schools. At both schools well over half the students receive subsidized meal assistance. The student population at School A is approximately 80% African American and the student population at School D is approximately 80% white. See Table C for the longitudinal display for each of the two schools.

Table C: Longitudinal Display 2003-2006



The steady climb in student achievement documented at these two schools suggests that teacher proficiency at implementing the curriculum program may be a contributing factor to improved student achievement.

New Jersey: External Evaluation—Educational Testing Service in Princeton, New Jersey is currently conducting an external evaluation of the implementation of the K-5 pre-engineering mathematics curriculum program for the Lawrence Township Public School system. An executive summary report was presented to the school board in August 2006 detailing results from the first year of implementation. The focus of the first year's evaluation was on the fidelity of implementation and on developing assessment items to measure student learning outcomes. The following items summarize the ETS report concerning the implementation of the program:

- The professional development sessions provided by the developers met the standards for high quality inquiry-based pedagogical training. Teachers, students, and parents were enthusiastic about the program.
- Classroom observations found teachers to be successful in implementing the curriculum program. Students had opportunities to communicate their understanding through discussion and writing. Students were often given the opportunity to work together in collaborative ways.
- Teachers used a variety of questions—both higher order and factual recall, which led to open discussions that provide opportunities for students to analyze and brainstorm about mathematical ideas.

Assessment measures were also developed and field tested during the fist year of implementation. ETS reported that a total 132 multiple-choice items and 36 open ended items were piloted with 245 students in the content areas of Algebra, Geometry, and Data Analysis. The constructed items were found to be similar in construct to the New Jersey assessment items on the statewide mathematics assessment ASK, thereby justifying their use.

Future Research Plans

During the field test phase of this project, two separate issues have influenced program development and revealed a need for further research. The first is the issue of implementation of the program. Fidelity of implementation logically should impact student achievement and thus a need to establish this relationship and to define effective implementation has emerged as a research consideration.

The second issue to emerge has been teacher mathematical knowledge. Implementation of the program has revealed misconceptions and deficiencies in teacher knowledge, not only to school leaders, but also to classroom teachers. Planning conversations consistently include clarification of mathematical ideas. Phone calls and emails to developers about mathematical topics in the lessons are common occurrences with teachers who are implementing the program. Thus a need to measure change in teacher mathematical knowledge has also become a research consideration worthy of exploration.

Fidelity of Implementation and Student Achievement—As schools implement the pre-engineering mathematics curriculum, which uses inquiry-based practices as its cornerstone, we expect to draw correlations at grade levels between fidelity of implementation and student achievement levels. The longitudinal data suggests a correlation between years of implementation and improved student achievement. We would like to examine to what extent instructional practices change during implementation over time. W expect that both teachers and students become more mathematically competent and proficient. The research questions that will guide the future work of this project are:

Question 1. Fidelity of Implementation—To what extent do grade levels of teachers *competently* implement Math Out of the Box® lessons?

Question 2. Student Achievement—To what extent do groups of students become more mathematically proficient as evidenced by *improved mathematics achievement* on independently designed assessment measures when the Math Out of the Box program is implemented at that grade level?

Question 3. Fidelity/Achievement Correlation—What is the resulting relationship at grade levels between *competent implementation* and *improved student achievement*?

Hypothesis: If teachers competently implement the Math Out of the Box lessons, then their students' become more mathematically proficient as evidenced by improved mathematics achievement on independently designed assessment measures.

Data will be collected from two school district sites in South Carolina. Partnerships between the development team and the two school districts have been established and continue through on-going interaction. Small pilot projects have been implemented and are ongoing at one or two select school sites in each of the districts. The number of elementary schools in each district ranges from eight (8) to twenty (20). The criteria for selection have previously been based on the academic needs of the schools. The lower performing schools in each district have been where field testing and piloting have taken place. It is expected that three schools, one in each district, that have not previously participated in the project will be included in the field testing and piloting of the Number strand, *Developing Number Concepts*. Selection criteria will vary among districts based upon administrative recommendations. Thus two different implementations will be available for each district—one new site using only the numbers strand, *Developing Number Concepts*, and one or more established sites using the complete curriculum program of four strands, *Developing Algebraic Thinking*, *Developing Geometric Logic*, *Developing Measurement Benchmarks*, and *Developing Number Concepts*.

For ***Question 1***, classroom observations will be conducted and data will be collected from other sources, including interviews and surveys. A grade level *fidelity of implementation composite score* will be developed based on observations, interviews, and survey results, hours spent in grade level planning for math during implementation, and hours spent in professional development activities related to the project (formal group sessions and individual "coaching" sessions with school leaders). All participating teachers will attend formal professional development workshops, formal reflection sessions with peers and school-based leaders, and weekly formal planning sessions with grade level team members. They will be observed at least twice during implementation. They will also complete surveys and participate in interviews.

An instructional analysis instrument, Five Dimensions of Instructional Practice (FDIP), designed by a member of the development team for the purpose of documenting fidelity of implementation of the curriculum will be used for analyzing and describing instructional practice in this project. (See Appendix A.) The instrument was designed based on a synthesis of information from mathematics educators (Skemp, 1978; Van de Walle, 2001), researchers (Ross et al., 2003; O'Donnell & King, 1999; Cooper, 1999), and philosophers (Ernest, 1988). The instrument has provided an effective and consistent basis for categorizing instructional practices in other research settings. Educational Testing Service (ETS) adapted the instrument for use in an independent evaluation of the fidelity of implementation in Lawrence Township Public Schools (LTPS) which further established the instrument's reliability in documenting instructional practice.

Multiple classroom observers have used the FDIP when analyzing common field notes. The instrument has been used in professional development workshops and the use of a common language for describing practice consistent with the instrument has been well established in these venues. The inquiry-based indicators found in the FDIP are consistent with the practices supported in the pre-engineering curriculum. Surveys and interviews will be designed in parallel to the FDIP, in order to solicit self analysis by the teacher concerning his/her instructional practice in language that is similar to that used in the FDIP. A method for quantifying the results of the interviews and surveys will be developed and these values will contribute to the overall grade level fidelity of implementation composite score.

School based leaders will assist in conducting classroom observations and will prepare transcripts of the observations. At least two project team members will independently quantify each transcript using the FDIP numerical scale of inquiry-based implementation. The quantification of observation transcripts performed independently by two team members reduces effects from subjectivity and helps secure a valid composite score for each observation. By adding together the five dimension quantities, a composite score for each transcript will be obtained.

The criteria that will be used to calculate the ***fidelity of implementation composite score*** is detailed in the Fidelity of Implementation Rubric (Appendix A). The grade level score will be the calculated mean of the individual teacher scores at the grade level. The Fidelity of Implementation Rubric will be field tested throughout the project to calibrate benchmark values and to help ensure the validity of the fidelity of implementation composite score.

For ***<u>Question 2</u>***, quantitative data will be collected and analyzed primarily from two different assessment sources, the South Carolina statewide assessment, Palmetto Achievement Challenge Test (PACT), and locally administered diagnostic assessments, such as MAP. The PACT assessment has been recognized as one of the best state accountability systems in the nation by the Princeton Review (2003). Because of its alignment with national standards, PACT can provide a reliable source of data concerning a student's overall mathematical proficiency. Because PACT does not provide diagnostic data, impact of individual content strands cannot be evaluated through PACT results. However, two levels of comparisons will be made for new sites in order to strengthen the claim that the intervention of Math Out of the Box is a causal factor in changes in PACT scores. See Table I for a summary of the two comparisons groups.

Two treatment populations will be used in the comparisons for new implementation sites: 1) the schools where the pre-engineering curriculum is used during the current school year but not in the previous school year (Intervention Schools); and 2) the schools where the curriculum is not used during the previous or the current school year (Non-intervention Schools). The first level of comparisons will be made *within* the two treatment populations, at each grade level, within each school, comparing previous year's scores to current year's scores. A rate of change will be calculated (see Table I) at each grade level, for each school, and a significance test will be applied to determine whether the change in scores, from the previous year to the current year, at each grade level within each school is statistically significant.

A second level of comparison will be made *between* matched-pairs of schools from the two treatment populations. Intervention schools will be paired with non-intervention schools based on comparable demographic variables (African Americans, whites, Hispanic, Subsidized Meal Assistance, etc.). A ratio of differences will be calculated for each pair (see Table D) and a significance test will be applied to determine whether the differences between the matched pairs are statistically significant.

Table D: Comparison Groups

Grade Level Scores→ ↓ Treatment Groups	Previous year's PACT scores (percent of students meeting standard at grade level) (PRE)	Current year's PACT scores (percent of students meeting standard at grade level) (CUR)	Rate of Change at grade level *within* schools between previous and current years' scores
Intervention Schools (IS)	PRE-IS	CUR-IS	<u>CUR-IS – PRE-IS</u> PRE-IS
Non-intervention Schools (NS)	PRE-NS	CUR-NS	<u>CUR-NS – PRE-NS</u> PRE-NS
Ratio of Differences *between* matched pairs of schools	<u>CUR-IS – PRE-IS</u> CUR-NS – PRE-NS		

If the change *within* an Intervention School is positively significantly different, and the difference ratio *between* the Intervention School and its matched Non-intervention School is also significantly different, with the Intervention School showing greater improvement than the non-Intervention school, then the claim is strengthened that the intervention curriculum program is a causal factor in the difference. By including two different sources of student achievement data, state mandated and local diagnostic assessments, the validity of the outcomes will be further strengthened.

At established sites, longitudinal data has been collected through classroom observations, surveys, and interviews. Also, student assessment scores are available. This data will be analyzed in order to further establish whether implementation improves over time and whether improved implementation contributes to improved student achievement.

For ***Question 3***, project researchers will match the fidelity of implementation composite score for each grade level team with the student achievement rate of change value for that grade level team. It is expected that competent and expert levels of implementation will be matched with positively significant changes in student achievement levels and that novice levels of implementation will be matched with no significant changes or negative changes is student achievement. By relating a grade level fidelity of implementation composite score to grade level student achievement, it is expected that this research project will contribute knowledge to the educational community concerning the unexplored relationship that exists between instructional practice (as supported by the implementation) and student learning.

Teacher Content Knowledge—Anecdotal data collected from sites where the pre-engineering mathematics curriculum program has been field tested and piloted indicate that teachers and school leaders begin to recognize misconceptions and deficiencies in their own mathematical knowledge. Email records, questions asked during formal professional development sessions, and phone logs provide strong evidence that mathematical conversations are taking place among teachers, school leaders, and curriculum developers as teachers grapple with their own understanding of the mathematical concepts they are teaching.

The previously discussed plan for data collection does not include a means for measuring change in teacher mathematical knowledge, which is also a future research consideration for this project. Classroom observation data shows evidence of missed teaching opportunities as well as misleading instruction because of misconceptions or deficiencies in knowledge held by teachers. The anecdotal data indicates that teachers are self-diagnosing this in many cases and seeking consultation to clarify their own understanding of specific mathematical ideas. However, no empirical evidence exists to verify that teachers are developing mathematically as a consequence of implementing the pre-engineering mathematics program.

To remedy this deficiency, it is our intention to develop a summative assessment derived primarily from measures of teachers' knowledge for teaching mathematics that are developed as part of the Learning Mathematics for Teaching (LMT) Project at the University of Michigan. Teacher learning outcomes, as measured by the LMT project items, will be the primary evidence used in evaluating change in teacher mathematical knowledge. The research design will be a non-experimental comparison design. The convenience sample for this study will consist of practicing teachers who are field testing or piloting specific curriculum units. A pre-test using the measures from the LMT project will be administered prior to implementation. The same form of the test will be administered as the post-test at the end of the semester. The time between the administration of the pre- and post-tests is expected to be sufficient to minimize test-retest effect. Scores from the pre- and post-tests will be compared using a dependent samples *t*-test. The effect size will be calculated to determine the strength and direction of the relationship between the intervention and the mean change in the teachers' knowledge for teaching mathematics. A *t*-ratio will also be calculated to determine the likelihood that the effect size is due to chance.

The LMT items are designed to measure teachers' mathematical knowledge for teaching in the content domains of number and operations; patterns, functions, and algebra; and geometry. The measures are designed to capture the extent to which teachers can address certain mathematical related scenarios that arise in teaching, such as: i) the evaluation of unusual solution methods; ii) the use of appropriate and accurate mathematical definitions and representations; iii) the identification of adequate (or inadequate) mathematical explanations; iv) identification of common error patterns; v) the anticipation of concept difficulty and/or complexity; and vi) the recognition of mathematical concepts that emerge from unusual, but accurate student strategies.

The LMT items have been piloted with thousands of elementary teachers, yielding information about item characteristics and overall scale reliabilities. LMT developers contend that items are suitable for evaluating: i) content-focused professional development projects, ii) studies examining teacher learning from pre-service coursework, iii) the impact of new curriculum materials, and iv) projects exploring the contribution of teacher knowledge to student achievement. Users have the option of using forms that have already been piloted and analyzed or of constructing their own form from the LMT item pool. With support from the National Science Foundation and the Department of Education and others, the LMT developers are conducting validation studies to compare teachers' performance on the LMT items with their actual classroom teaching. LMT developers have also conducted cognitive tracing interviews for specific items and item mapping against NCTM and other state standards. (The LMT information provided here is a summary of information found on the LMT web-site retrieved 11/07/06: http://sitemaker.umich.edu/lmt/about)

Summary

A pre-engineering mathematics curriculum program at the K-5 level is long overdue. If middle and high school students are to be prepared for STEM course work, the foundation must be laid at the elementary levels. This paper outlines the design considerations that form the basis for the K-5 pre-engineering mathematics curriculum program presented here. The design considerations are informed by the post-secondary educational research conducted by Felder and Brent and based on the STAR Legacy learning cycle developed for engineering education at Vanderbilt University.

Preliminary results suggests that students from high poverty communities show steady improvements as their teachers become more experienced with implementing the program. The curriculum program supports teachers in changing their instructional practices from transferring knowledge *to students*, to building knowledge *with students*. Anecdotal records indicate that teachers begin to self-assess their own deficiencies and misconceptions in mathematical content and seek support from their peers, school leaders, and outside content sources.

Future research plans include relating the fidelity of implementation of the program to student learning outcomes. In addition, teacher learning will be examined and a method of measuring teacher learning outcomes will be explored.

Appendix

Comparison of the Legacy™ Cycle and the Math Out of the Box™ Cycle

<table>
<tr><th>Legacy Learning Cycle™</th><th>Supportive Research</th><th>K-5 Pre-Engineering Mathematics Learning Cycle™</th></tr>
<tr><td>Challenge
Each cycle begins with a Challenge, a realistic scenario that educational professionals may encounter.</td><td rowspan="2">Experts in cognitive science and brain research (e.g., Anderson, Reder, & Simon, 1998; Wolfe, 2001) emphasize the retentive importance of connecting new knowledge to prior knowledge. The Challenge is an effective instructional method, based on cognitive research, that anchors specific content around challenges that serve as entry points into a series of learning activities (Brophy, 2000).</td><td rowspan="2">Engage
The Engage phase of the pre-engineering learning cycle encompasses the first two phases of the Legacy Learning Cycle. In this phase, teachers present a scenario (Challenge) to students to solicit their original thoughts (Initial Thoughts) concerning the topic. This phase is designed to allow students with varying prior experiences and abilities to connect between past and present learning experiences. Such connections provide natural pre-assessment opportunities for both teachers and students. By soliciting prior knowledge during the Engage phase of the learning cycle, the lesson design embeds instructional strategies that support the research of what is known about how people learn.</td></tr>
<tr><td>Initial Thoughts
The Initial Thoughts component gives students the opportunity to explore what they currently know about the opening scenario, even if their initial responses to the Challenge are naïve.</td></tr>
<tr><td rowspan="2">Perspectives and Resources
The Perspectives and Resources phase of the cycle is presented within the context of a "real-life" situation. Consequently, most students immediately see the relevance of the content provided here. Through a series of activities and materials students use the content of the module to investigate resources that are pertinent to the topic and to learn different perspectives, both of experts and peers.</td><td>This phase of the cycle is based on “the cognitive principle of assimilation which implies that understanding cannot be imposed” upon learners but instead must “progress developmentally” from concrete to abstract opportunities (Baroody & Ginsburg, 1990, pp.56-57).</td><td>Investigate
The Investigate phase of the pre-engineering learning cycle provides students with common, concrete experiences that challenge them to solve problems and investigate mathematical ideas. Information is gathered, patterns are observed and analyzed, connections are made and applied, and conclusions are drawn and defended. As patterns are observed and connections made, students engage in mathematical reasoning and problem solving that support conceptual understanding and procedural development.</td></tr>
<tr><td rowspan="2">Schon (1983) described two types of reflection—reflection-in-action, which is known as “thinking on our feet,” and reflection-on-action, which involves exploring why we think the way we do. This linked process of reflection, in-action and on-action, compels students to take responsibility for their learning.</td><td>Reflect (in-action)
The learning cycle structure provides for continuous reflection-in-action as students represent, verbally communicate, and compare their findings throughout each lesson.</td></tr>
<tr><td rowspan="2">Assessment The Assessment phase provides students the opportunity to apply what they know and to identify those topics requiring additional study. They are encouraged to return to the module's resources to re-study content until they are able to solve the opening challenge.</td><td>Reflect (on-action)
The Reflect phase of the learning cycle provides an opportunity for focused reflection-on-action as students are asked to examine and explain their thinking by writing about what and how they have learned.</td></tr>
<tr><td rowspan="2">Singley and Anderson (1989) argued that application, or transfer between tasks, is a function of the number of different representations and opportunities to engage available to students over a course of study. Providing students with opportunities to investigate a variety of representations and to engage in numerous tasks with a similar focus secures the transfer of learning.</td><td rowspan="2">Apply
As the information gathering process comes together, students make connections to past learning, new knowledge, and real world experiences. Students are far more likely to retain their ideas and concepts as they begin to see patterns and make connections to their knowledge of the world. Students are challenged to apply their knowledge to new or different situations and to explore broader or deeper applications of their discoveries. In the Apply phase of the cycle, both students and teachers can assess the depth of understanding of the newly formed ideas, as the knowledge gained is connected to new learning—and the cycle of learning begins again.</td></tr>
<tr><td>Publish The Publish phase concludes the module lesson. Students make public what they have learned through presentations, written papers, or online postings. Students are expected to use this opportunity to reflect upon their initial thoughts and assess the learning that has occurred throughout the Legacy Cycle.</td></tr>
</table>

Five Dimensions of Instructional Practice

Traditional	Dimensions of Practice	Inquiry-based

D1: Teacher's conceptions of math as a discipline

Traditional	Inquiry-based
a. Emphasis on procedures and "basic facts" in teaching. b. A belief that skill mastery implies mathematical understanding. c. Using or teaching a single strategy for solving certain types of problems. d. Seeing mathematics as a checklist of topics or procedures to learn.	a. Emphasis on conceptual development in teaching. b. Explaining ideas using a variety of representations implies mathematical understanding. c. Recognizing connections that lead to the use of multiple strategies to solve problems. d. Seeing mathematics as a coherent body of knowledge, relating to everything—as a means to understanding and describing the world.

D2: Students' tasks

Traditional	Inquiry-based
a. Problems have a single solution and a single path to the solution is presented. b. A problem may have multiple paths for reaching a solution, but the teacher demonstrates and encourages the use of a particular path over all others. c. Lesson tasks tend to provide practice at replicating a single method. d. Students are expected to use particular paths to solve particular problems and are given little autonomy exploring new paths for solving problems.	a. Problems and tasks are designed to have multiple solutions and/or multiple paths for getting to a single solution. b. Students are encouraged to share and compare strategies for solving problems. c. Lesson tasks involve both reasoning and proof in the development of mathematical ideas. d. Students have autonomy within defined parameters to discover, explore, and create multiple paths to solutions.

D3: Teacher's role in curriculum implementation

Traditional	Inquiry-based
a. The teacher practices a model of transmitting content to the students through instructional strategies of "telling" and "demonstration." b. The teacher is considered the expert and she "explains" and directs how things should be done. c. The content of the lesson is focused on teacher defined and demonstrated procedures that students are expected to replicate. d. The teacher's questions focus on students' ability to replicate previously defined procedures and facts, and to provide correct final answers. e. The process standards may be included in the lesson, but the process itself is not used for the construction of knowledge—it is just another way of performing a known procedure. f. The teacher evaluates the students' work and answers for accuracy.	a. The teacher uses "indirect" strategies for instruction, allowing students to explore and investigate ideas within defined parameters and provides clarification and summarization of ideas as appropriate. b. The teacher acts in several different roles including facilitator, questioner, and co-learner. c. The content of the lesson is focused on development of a mathematical idea that students explore and investigate through a variety of means. d. The teacher's questions focus on student thinking in the development of new ideas and on probing for the logic and reasoning that lie behind the answers. e. The process standards are used as a means for investigating and exploring mathematical ideas in order to construct knowledge. f. The teacher assesses students' work and students' comments for understanding.

D4: Student interactions and confidence

Traditional	Inquiry-based
a. Most interactions that occur in the classroom are teacher to student or student to teacher. b. Students do not recognize peers as sources of mathematical information. c. The teacher views group work primarily as an opportunity to develop social skills or as a necessity for sharing materials. d. Students rely upon the teacher for judgment of quality and accuracy of work.	a. Interactions are a blend of student to student, student to teacher, and teacher to student. b. Students recognize themselves and their peers as sources of mathematical information. c. The teacher values the culture of group work as an environment for learning. d. Students and teachers have confidence in students' ability to assess the quality and accuracy of and their peers' work.

D5: Use of manipulatives and other tools in classroom

Traditional	Inquiry-based
a. Materials are used by the teacher for demonstrating a specific procedure to be used in generating answers. b. The teacher directs and prescribes the use of materials and students replicate the actions of the teacher. c. Materials are viewed by the teacher as the "concrete" step that leads to "pencil and paper" abstraction—as a concrete "crutch" needed by "low level" students who cannot do the "abstract" pencil and paper work.	a. When materials are used by teachers for demonstration purposes, it is either to define parameters of proper use or to explore an idea collectively as a whole class. b. Students have access to materials in order to explore and investigate mathematical solution paths, relationships, and connections. c. Materials are viewed by the teacher as "thinker toys" used by students to explore new ideas, or as "assessment tools" used by students to demonstrate constructed knowledge.

Dimensions Rubric

Teacher Name:________________________ Grade:___________Date:_______________

Use the 5 Dimensions of Instructional Practice Instrument. Circle the number beside each D1, D2, D3, D4, and D5 below based on the following criteria:

1 If only traditional indicators are present
2 If both traditional and inquiry indicators are present, but more traditional than inquiry
3 If an equal number of traditional and inquiry indicators are present
4 If both traditional and inquiry indicators are present, but more inquiry than traditional
5 If only inquiry indicators are present

D1:	**1**	**2**	**3**	**4**	**5**
D2:	**1**	**2**	**3**	**4**	**5**
D3:	**1**	**2**	**3**	**4**	**5**
D4:	**1**	**2**	**3**	**4**	**5**
D5:	**1**	**2**	**3**	**4**	**5**

Fidelity of Implementation Rubric

Data Source	Method of Quantification	Established Benchmarks
Observations *Observation Score=O*	The *Five Dimensions of Instructional Practice (FDIP)* rubric will be used to categorize instructional practice in terms of "inquiry-based" and "traditional". Each of the five dimension will be scored by the following system: 1—all traditional practices observed 2—both inquiry and traditional practices observed, but more traditional than inquiry 3—equal amounts of traditional and inquiry practices observed 4—both inquiry and traditional practices observed, but more inquiry than traditional 5—all inquiry practices observed The Observation score (O) will be the total of the five dimension scores.	Novice Range 0-10 Competent Range 11-19 Expert Range 20-25
Interviews *Interview Score = I*	Each of the five dimensions of the FDIP will be framed as a question. Participant responses will be coded based on the indicators in the FDIP rubric. The same scoring system will be applied to the coded results for each dimension. The Interview score (I) will be the total of the five dimension scores.	Novice Range 0-10 Competent Range 11-19 Expert Range 20-25
Surveys *Survey Score = S*	A retrospective pre/post survey will be developed based on the indicators found in the FDIP rubric. The same scoring system will be applied to both the pre and the post responses. A pre total and a post total survey score will be calculated. A ratio of the post-total to the pre-total will be calculated to determine the Survey score (S). *Note: These ratios are based on the assumption that teachers' "pre" practices are predominantly traditional.*	Novice Range Less than 1.1 Competent Range $1.1 \leq S \leq 1.3$ Expert Range Greater than 1.3
Professional Development Sessions *Professional Development Score= D*	Two professional development sessions consisting of approximately 12 contact hours will be provided to teachers. Teachers who attend both sessions will receive a Professional Development score (D) of 12, teachers who attend 1 session will receive a 6, and teachers who attend neither session will receive a 0.	Novice 0 Competent 6 Expert 12
Grade Level Planning Sessions *Planning Score = P*	It is expected that teachers will meet at least one hour weekly during the implementation of the unit for grade level planning. The unit consists of 60 lessons, which will require approximately 12 weeks of instruction. The number of hours that the teacher meets with her grade level team will determine the Planning score (P).	Novice Less than 6 Competent $6 < P < 9$ Expert Greater than 9
Formal Coaching Sessions *Coaching Score = C*	In schools that have a math coach, it is expected that teachers will meet individually or in small groups with the coach (in addition to the weekly planning) to participate in formal weekly coaching sessions during the unit implementation. The number of formally scheduled and attended coaching sessions will determine the Coaching score (C).	Novice Less than or equal to 2 Competent $2 < C \leq 4$ Expert Greater than or equal to 5

Fidelity of Implementation Composite Score (CS)= O+I+S+D+P+C

Novice Range: 0-29 *A Composite Score that falls within the novice range indicates that inquiry-based practices are not typically used by the teacher.*

Competent Range: 29 < CS < 58 *A Composite Score that falls within the competent range indicates that both inquiry-based and traditional practices are regularly used by the teacher.*

Expert Range: Greater than or equal to 58 *A Composite Score that falls in the expert range indicates that inquiry-based practices are predominantly used by the teacher.*