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Using the E in STEM as a Catalyst for Science and Mathematics Curriculum Reform in a Large School District

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Abstract

The *Engaging Youth through Engineering (EYE)* Modules are being developed as the middle grades part of a current K-12 partnership driven effort to meet a community's 21st century workforce needs. One purpose of the middle grades *EYE* Modules, besides positively impacting students' beliefs and performance related to STEM (Science, Technology, Engineering and Mathematics), is to serve as a catalyst for district level STEM reform. "STEM reform" related to the *EYE* Modules is defined as local curriculum standards that require using engineering design challenges and the related design process to integrate required mathematics and science content for all middle grades students as they develop solutions to problems of relevance in the world today. Engineering is defined "to mean any engagement in a systematic practice of design to achieve solutions to particular human problems." [1] As part of a current National Science Foundation award, a longitudinal comparison study of the impact of the *EYE* Modules is underway and will be completed in 2014. In addition to early indications of the Modules' impact on students and teachers, one impressive result is the impact of the Modules on the large, diverse school district (65,000 students, 100 schools, 70% poverty, 50% African American) and its decision to reform its science and mathematics curricula to now require the implementation of engineering design challenges as the integrator of the STEM disciplines.

Introduction

Numerous reports, beginning with *Rising Above the Gathering Storm*[2] (and more recently from the President's Council of Advisors on Science and Technology (PCAST)[3 & 4], have raised our nation's awareness of the dire need to transform K-12 education in order to prepare and inspire the vast numbers of K-12 students needed to meet our nation's STEM-dependent workforce needs. In the summer of 2006, to address and rise above one city's own "gathering storm," business and community leaders approached the Mobile Area Education Foundation (MAEF) and requested their leadership in addressing K-12 issues related to STEM workforce needs for the region. Following a year of collaboration and planning, a pilot initiative emerged called *Engaging Youth through Engineering* or *EYE*. The goal of *EYE* was and still is to engage area youth in grades 4-9 in science, technology, engineering and mathematics (STEM) academics and careers by providing students with a coordinated continuum of curricular and extra-curricular experiences that use real life engineering design challenges as a "hook." Once "hooked," and with careful guidance and support of "adult influencers" (teachers, counselors, parents, and business volunteers), the theory of action is that youth will become motivated and choose to take the high school mathematics and science coursework needed in preparation for STEM post-secondary study and careers, but not required by the district or the state.

The *EYE* curriculum at all levels promotes student outcomes which are closely aligned with those often mentioned as 21st century learning skills as well as the Accreditation Board for Engineering and Technology (ABET) standards that are used to evaluate post-secondary engineering schools and colleges[5]:

- Apply knowledge of mathematics, science and technology through the engineering design process.
- Analyze and interpret data when presented in multiple forms.
- Identify, formulate and solve problems.
- Communicate effectively.
- Function as part of a multidisciplinary team.
- Use the techniques, skills and tools necessary in the modern workforce.
- Recognize the need for, and engage in, ongoing learning.

Table 1

***Engaging Youth through Engineering (EYE)* Strategies**

Elementary School Level (4th & 5th Graders)	**Middle School Level (6th, 7th, & 8th Graders)**	**High School Level (9th-12th Graders)**
• *EYE* Clubs • *EYE* Summer Camps	• *EYE* Modules • “Career Explorations” Lab Course • Robotics Clubs	• “Engineering the Future” Course • Robotics Competitions

EYE includes both curricular and extra-curricular strategies that are implemented at elementary, middle, and high school levels, as is seen in **Table 1**. At the elementary level *EYE* uses the *Engineering is Elementary* curriculum developed by the Museum of Science (MOS), Boston in its extra-curricular clubs and camps and uses *Engineering the Future*, also developed by the MOS, for its high school project-based physical science elective course.[6 & 7] For the middle grades the design of *EYE* includes implementation of engineering based modules as part of the core curriculum, in every math and science class, in order to ensure every student experiences and is impacted by *EYE*. The *EYE* planning team was adamant that the curriculum involve math, as well as science classes, because student engagement and achievement in mathematics is a major barrier to students succeeding in high school coursework needed for STEM careers. Thus the *EYE* middle grades curriculum had to support the existing state and district curriculum requirements for both math and science. However, a review of existing curricula revealed that no middle grades engineering-focused materials existed that included mathematics and that matched the district’s required mathematics and science standards. Therefore, the inquiry-based *EYE* Modules had to be developed by the MAEF, which identified a team of STEM professionals and curriculum developers, including engineers and engineering education professionals.

The *EYE* Modules

The *EYE* Modules are a set of eight comprehensive and extensive instructional guides for middle grades math and science teachers to implement through collaboration in both mathematics and science classes. Each Module provides students with opportunities to engineer solutions to interesting problems relevant today through hands on and practical applications. They address STEM content and practices that fill gaps between state-mandated and tested content and what business and industry say they need, including innovative problem solving, communication and teamwork skills. Module specific professional development and implementation kits accompany each Module. **Table 2** provides a list of *EYE* Modules. The set of 8 Modules with their grade level "Launcher" lessons involve about 50 hours of STEM exposure. Each *EYE* Module requires a combination of 6 to 8 hours of class time and 1) addresses an engineering design challenge around issues related to National Academy of Engineering's (NAE) Grand Challenges for Engineering[8]; 2) fosters the development of an "engineering habit of mind;" 3) integrates technology and other resources to engage and meet the needs of diverse middle grades students, and 4) deepens understanding of mathematics and science content, with an emphasis on mathematics. The Modules *are not* a complete engineering, technology or STEM curriculum; rather they are a supplement to and support the existing mathematics and science curriculum. They *are* a set of comprehensive and extensive instructional guides that use design challenges and the engineering design process to engage middle grades students in pursuing STEM careers and academics.

Table 2. *EYE* Modules

6th Grade Finalized in 2011	7th Grade Finalized in 2012	8th Grade To be Finalized in 2013
6th Grade Launcher	*7th Grade Launcher*	*8th Grade Launcher*
Harnessing the Wind- Engineering & Siting Wind Farms	*EYE on Mars* Designing ET Growth Chambers	*Designing Eco-friendly Plastics* A Chemical Engineering Module
	To Puppies and Beyond! A Genetic Engineering Module	*Let's Get Moving*! Engineering Jet Powered Cars
Don't Go with the Flow Solving Sediment Discharge Issues	*Catch Me if You Can!* Engineering Blood Clot Filters	*Up and Down and All Around* Designing Roller Coasters

The design of the *EYE* Modules is built on the **theoretical foundation** of the four components of the "How People Learn" model.[9]

- Instruction needs to be learner centered, building on prior knowledge, motivation, and interests.
- Instruction needs to be knowledge centered, use cognitive and social constructivist approaches that help foster deep understanding of content.
- Instruction needs to be assessment centered, focusing on formative assessments that help students and teachers visualize complex processes.
- Instruction takes place within communities and needs to be connected to the broader community.

General design principles have guided the development of each *EYE* Module, including:

- Learning outcomes and a driving question, coupled with Wiggins and McTighe's "backwards design" process, guide the development of all materials. [10 & 11]
- An engineering design challenge featuring industry and social issues of relevance to students provides the unifying theme and "hook" for each module, highlighting the "why bother" of learning mathematics and science.[12 & 13]
- Modules systematically develop team work/communication skills.[14& 15]

- The engineering design challenges involve technology, equipment and materials in the applications of mathematics and science content, promoting an integrated STEM curriculum.[16]

Doug Clements' Curriculum Research Framework [17] has guided the research and development cycle of the *EYE* Modules. Consistent with that framework, there have been multiple phases of formative development and research that include field testing with multiple levels of review and feedback. The MCPSS identified two middle schools to serve as the research and development schools for the *EYE* Modules, as well as a demographically matched comparison school for each *EYE* R&D school. Science and mathematics curriculum supervisors as well as the teachers at the two *EYE* R&D schools have been active participants in the development of the Modules, contributing to the identification of Module content, providing feedback during the initial drafting of the Modules and following the implementation of each pilot and field test edition. The set of eight *EYE* Modules has developed gradually with early pilot versions of some of the Modules being implemented as early as 2007-2008. Revisions to all editions of the Modules have drawn heavily on the suggestions made by teachers. Final editions of the Modules include revisions that incorporate the Common Core State Standards for Mathematics, which was adopted in 2010 by the state under the name Career and College Ready Standards.[18]

Implementation and Professional Development Model for the *EYE* Modules

The implementation model for the *EYE* Modules during the research and development phase included professional development and significant support for the implementing teachers in the two R&D middle schools. An *EYE* Coach was assigned to each school during each Module's implementation who provided support in numerous ways: co-leading professional development to prepare teachers for implementation; coordinating scheduling of the Modules' implementation with the school district and school level administration and teachers; preparing materials, which included assembling "baggies" of materials needed for teams and setting up equipment and technology needed for investigations; troubleshooting instructional technology issues related to audio-visual and other media incorporated in the Modules; securing and coordinating of volunteers from business and the area college of engineering to provide support for the teachers during the more labor-intensive lessons and to interact with students. In addition the *EYE* Coach served as a valuable resource to the Module development team in providing additional implementation feedback which influenced revisions incorporated in subsequent editions of the Module.

Each *EYE* Module is carefully designed to involve the application and integration of required grade-level mathematics and science content as students tackle the Module's engineering design challenge. Both mathematics and science teachers need to understand the big ideas of the content integrated from both disciplines, as well as the engineering content. Thus, each Module's implementation includes a full day of Module-specific professional development.

EYE Module Longitudinal Study Methodology and Instrumentation

Participants and Basic Research Design A longitudinal comparison study of the impact of the finalized set of the *EYE* Modules is following a cohort of students who were sixth graders in

2011 and will complete the eighth grade and the set of all eight *EYE* Modules in 2014. *EYE* has also been following cohorts of students receiving draft editions of the *EYE* Modules fall 2009.

The longitudinal study has involved middle school students in two *EYE* schools and two matched comparison schools. One *EYE* school is a magnet math and science school and one is a "regular" school; the magnet school is matched with an arts magnet and the regular school is matched with another "regular" school. Because the magnet schools are so different in emphasis, we have been focusing our studies of the efficacy of the Modules on a comparison between the two fairly closely matched "regular" middle schools. Overall, the two schools have similar levels of achievement and over half of the students in both schools receive free lunch. However, the school that has had the Modules has a larger minority population (around 50 percent versus 30% African-American. The exact size of the schools varies from year to year, but in general the number of students in each cohort averages around 320 per middle school grade level (grades 6, 7, & 8). Specific analyses vary depending upon the variables controlled for, e.g., covarying out 6^{th} grade scores when comparing 8^{th} graders, and attendance when assessments are implemented. As the analysis involves nonequivalent group comparisons, when we have the opportunity to control for prior achievement or beliefs, we attempted to do so. For early cohorts, our ability to match up prior data was complicated by problems in coding identification numbers.

Because the research of the Modules has involved developing the Modules as well as studying their impact, students from different cohorts have been exposed to different numbers of Modules at various stages of completion. The 2011-12 cohort that completes middle school in 2013-2014 is the cohort that will experience all of the Modules in their complete form. Hence, we expect our strongest findings to surround that cohort. However, as we will note below, there are impacts even for earlier cohorts with less complete versions.

Instruments Related to STEM Beliefs, Student Achievement and Engineering Design

We have used both existing instruments and others developed by the research team in the context of the study. A description of the set of instruments is below.

<u>STEM Beliefs, Efficacy, and Career Interest</u> A majority of our attitude and belief data come from a revised version of scales developed by the Assessing Men and Women in Engineering (AWE) web site.[19] We have developed summated rating scales using exploratory factor analysis techniques and analysis of the content of the items when possible. The questionnaire given at the beginning of 6^{th} and then again at the end of 8^{th} grade has items related to interests in STEM, attitudes toward STEM, knowledge of engineering, efficacy beliefs surrounding STEM, and items related to careers and high school course taking.

<u>Standardized Student Achievement</u> The school district has assessed students on the Stanford Achievement Test 10^{th} Edition (SAT-10), the Alabama Reading and Mathematics Test (ARMT), and, in addition for 8^{th} graders only, the ACT Explore assessment. Our focus for the SAT-10 and ARMT has been on mathematics scores related to specific content objectives that relate to *EYE* Modules rather than on overall scores. In particular, we have focused on the areas of data analysis and statistics. The SAT-10 was discontinued in 2011-12, so when we examine our cohort who has had access to the complete set of Modules, we will have only the ARMT data.

Engineering Design We have emphasized throughout the Modules the engineering design process. Because there were few measures related to engineering design developed for middle school students, we used the work of Bailey and Szabo[20] on evaluating design processes and Atman, et al.[21], to design an exercise that we believe addresses elements of the design process. Bailey and Szabo[20] focus how students evaluate design processes. Our assessment includes such an evaluation. Atman et al.[21], focus on the breadth and depth of thinking surrounding a design problem. Other questions we asked are an effort to ascertain the breadth and depth of thinking about a problem by our *EYE* students. We gave this to our 2011-12 cohort of 6th graders as they started 7th grade (after either having or not having two *EYE* Modules in 6th grade). We ask a series of questions about a design scenario. Our first scenario involves solving a litter problem that shows up after moderate to heavy rains on a tidal river. The students respond to questions related to:

1. What questions they would ask to help solve the problem.
2. Who they would want on their team for solving it.
3. Whether a proposed design for solving the problem is adequate.
4. How a set of graphs might help in solving the problem.
5. What additional research they would have to do to solve the problem.

So far, we have only analyzed the results for the third question that asks students to evaluate a design process. We are currently working to refine the scoring of the entire exercise to include a rubric so that we can adequately address the overall set of responses that students make concerning all of the questions.

Results

Below we present analyses of data from the 2011-12 school year. One set of results involves examining the cohort of students who experienced early drafts of some of the Modules in the 6th, 7th, and 8th grades. The results presented compare 8th graders in the regular *EYE* middle school versus the comparison school. The other groups examined are the students in the cohort where *EYE* students are experiencing all of the finalized versions of the Modules and who were in the sixth grade in 2011-12. We examined their work on the engineering design process assessment that we have recently developed. Along with examining student impacts, we also present the more qualitative evidence of impacts on teachers and the district.

Impact on Students

STEM Career Interest and Awareness Based on the modified AWE[19] questionnaire, we developed a scale based on exploratory factor analysis that looked at how much students valued STEM related careers. There were four items included on a 1 to 4 scale, with a 1 indicating that it was not an important part of their future work and a 4 indicating that it was important to them; its internal consistency reliability was 0.68. We carried out an independent t-test to compare *EYE* students to the non-*EYE* school students and found that *EYE* students from the 2011-12 8th grade cohort value work that fits with descriptions of STEM careers ($M = 2.78$, $SD = 0.67$) more than the comparison school students ($M = 2.63$, $SD = 0.67$ with $t(537) = 2.48$, $p < .02$, *Cohen's d*

=0.22). They scored higher on this scale, but not on scales related to valuing personal satisfaction and power/prestige in a job. A second scale that we developed involved a set of items related to perceived efficacy of students surrounding design. The scale of four items ranged from 1 (low efficacy) to 4 (high efficacy) and had an internal consistency reliability of 0.72. We found students in that cohort were more confident in their ability to carry out the design process (M =2 .48, SD= 0.76 for *EYE* and M = 2.29, SD = 0.70 for comparison school, $t(517) = 3.09$, $p < .01$, *Cohen's d* = 0.27).

The students in the *EYE* school were more likely to report that someone had talked to them about the importance of mathematics to STEM careers (84% vs. 76%, chi-Square = 5.26, p < .03, Phi = .10), the importance of course taking choices to college readiness (91% vs. 84%, Chi-Square = 5.30, p < .03, Phi = .10), and were more likely to indicate an interest in an engineering major than students in the comparison school (25% vs. 17%, Chi-Square = 4.15, p < .05, Phi = .09). Each of these effects are small, but are large enough to be statistically different.

Standardized Test Results We focused our analyses of standardized tests on data analysis and statistics related objectives on the ARMT and the SAT-10 because that is a content area that is addressed across multiple Modules and grade levels. On the SAT-10 these strands were scored as below average, average, or above average. For our 2010-11 cohort of 8^{th} graders, we found that fewer of the special education students in the *EYE* school were in the below average category than in the comparison school (21% vs. 42%, Chi-Square = 4.12, $P < .05$, *Phi* = .21). We also found that 8th grade African-American students in our *EYE* school were more likely to score above average on the strand (39% vs. 20%) and less likely to score below average (11% vs. 33%) in the comparison school (Chi-square = 26.19, $P < .001$, *Cramer's Phi* = .29). The same pattern appeared on the ARMT in the 2010-11 Cohort for ethnicity, with African Americans at the *EYE* school scoring significantly higher than African American students at the comparison school (M = 53%, SD = 20.54 vs. M = 44%, SD = 21.55, $t(266) = 3.18$, *Cohen's d* = 0.42) These differences were true, even though there was no overall score differences on the overall tests. The district dropped the SAT-10, so we could not follow up that analysis in 2011-12. Analyses with our 2011-12 cohort on the ARMT did not, however, show statistical significance because of a change in the tested items focusing on a new area that was not connected with EYE. The only science testing we have access to is the 7^{th} grade Alabama Science Assessment that focuses on life sciences. We examined two concepts that appear in EYE modules (biotic versus abiotic, and Mendelian genetics). We found that the regular education (although not special education) students in the EYE school scored higher on the Mendelian genetics items (M = 61%, SD = 30.44 vs M = 55, SD = 30.83, $t(517) = 2.12$, p < .04, *Cohen's d* = .19) but not on the biotic versus abiotic items. We continue to explore the standardized tests, but feel that they sometimes do not capture the specific impact of EYE because of limited item sampling and the difference in focus that has been associated with tests developed during the No Child Left Behind era. As we continue to move into assessment of the Common Core standards in Alabama, we expect a better match between standardized assessments and EYE. We have also begun to develop and test out our own assessments to capture more directly the impact of EYE. Below we describe results from one of those assessments.

Engineering Design Process Assessment As noted earlier we have recently started to examine the 2011-12 cohort of 6^{th} graders as they gain experience with *EYE*. The process of engineering design is one area we expect them to show a difference in knowledge related to the comparison students. The design assessment was constructed so we could explore students' ability to demonstrate engineering habits of mind, e.g., the ability to think in a systems-like way, to recognize flaws in a design plan, to determine the usefulness of data in solving a problem, and to identify additional research needed. This assessment was administered to 401 students (189 *EYE* and 212 Comparison students) following the completion of the 6th grade Modules. In our initial analysis, we focused on student recognition of the flaws in a design process by analyzing the question that asked students to evaluate a design process undertaken to solve the problem. We found that *EYE* students were almost six times more likely than comparison students to identify and describe the need for revision and more research (23% vs. 4%, Chi-Square = 27.05, $p < .0001$, *Phi* = .27). Again the effect is small, but this is for students who have only experienced the two 6th grade Modules. We are currently working to develop a more sophisticated scoring system that will look at the entire exercise rather than just the design evaluation component. And we are working on additional Engineering Design Process assessment tasks to administer as this cohort of students complete the set of 7th grade and 8th grade Modules.

Impact on Teachers

Qualitative data, such as self-reports from *EYE* teachers, indicate that one of the most powerful outcomes of the Modules for teachers is the new collaboration between the mathematics and science teachers. Interviews with *EYE* Coaches supporting those teachers also highlight this new collaboration between the departments. Even as the *EYE* Coach support is being minimized as the current Study is drawing to a close, the Coaches and principals report that the teacher collaboration is continuing. In addition, having students work collaboratively in teams was a first for many teachers, especially the mathematics teachers. As a result of teaming and the Modules, teachers report they now see strengths in many of their students that previously had gone unrecognized, specifically the special education students; they often became the team leaders, gaining newfound respect from their classmates.

Impact on EYE on STEM Reform

One compelling summative finding has already emerged from the Study: the Modules have served as a catalyst for MCPSS to initiate STEM reform. Two data points support that finding. First, the school district has developed and implemented a STEM Improvement Program that includes revised mathematics and science standards now requiring the implementation of multi-day integrated "STEM Challenge" lessons quarterly in every middle grade math and science classroom across the district's 17 middle schools. In a letter to the director of *EYE*, the MCPSS superintendent acknowledged the impact of the *EYE* Modules as follows:

> *The EYE Modules, developed over the past five years and field tested and researched in two MCPSS middle schools, have been an important part of the MCPSS's focus on STEM. They have served as a catalyst for new STEM standards and policy as part of the MCPSS STEM Improvement Program (Peek, November 28, 2012).*

Second, in the fall of 2012 the school district hired a new district level STEM Resource Teacher, a master *EYE* teacher from one of the *EYE* R&D schools, to ensure that the district's STEM reform efforts, including the *EYE* Modules, are sustained, supported, and expanded. Not only did the district establish the new position, they assigned the newly hired STEM Resource Teacher to the *EYE* team for one full year to both gain an in-depth knowledge of STEM and understand better how to use engineering and engineering design challenges to bring relevance to STEM content and better prepare students for the area's workforce needs.

Conclusions

There is an urgent call for reform of K-12 teaching and learning of STEM subjects so that significantly more high school graduates are inspired and prepared to pursue the coursework required to meet the nation's demand for STEM-capable workers. To meet this growing demand for STEM-capable workers, school districts across the nation need to ensure that all students experience engaging STEM curricula involving hands-on and practical applications that bring relevance and rigor to core mathematics and science content motivating more students to take higher levels of STEM coursework in preparation for STEM-dependent careers. A reform of core required mathematics and science courses to include integrated STEM content, especially at the middle grades, is one strategy that insures that the needed reform impacts all students.

Our current *EYE* Module research results provide indications that using modules centered around carefully developed engineering design challenges is a successful strategy to integrate and bring relevance to the STEM disciplines at the middle grades level for all students. Our body of data is growing that supports the efficacy of using engineering focused modules, supported by well-developed instructional guides and professional development, to inspire and prepare middle grades students to pursue STEM careers, including students often under-represented in STEM careers. And, we anticipate even stronger data to emerge as the longitudinal study is completed that is following students who are experiencing the final complete set of eight *EYE* Modules.

We are also seeing that implementing a curriculum that capitalizes on the E in STEM to engage and inspire all students can also serve as a catalyst for district-wide curriculum reform being called for by PCAST[3 & 4] and others in order to meet our nation's workforce and economic needs. Providing districts with well-developed STEM instructional materials for implementation that is part of the required curriculum and is accompanied by professional development may be just what is needed to help districts to launch this urgently needed STEM reform. We have certainly seen one large urban district take important steps, as a result of implementing the *EYE* Modules, to transition beyond the traditional silos of science and mathematics as separate content divisions toward a structure that fosters a more integrated and relevant STEM-focus curriculum.

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