AC 2012-4850: ON THE BENEFITS OF USING THE ENGINEERING DESIGN PROCESS TO FRAME PROJECT-BASED OUTREACH AND TO RECRUIT SECONDARY STUDENTS TO STEM MAJORS AND STEM CAREERS

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On the Benefits of Using the Engineering Design Process to Frame Project-Based Outreach and to Recruit Secondary Students to STEM Majors and STEM Careers

Abstract

The pedagogical premise of our outreach program is project-based learning. Although there is some variation in the literature as to what elements of an intervention are required in order for it to be considered "project-based learning,"[1,2] there seem to be some essential components.[3,4] Land and Zembal-Saul[3] have described these (citing Blumenfeld et al.[4]) as follows: 1) "use of long-term investigations that emphasize iterative and progressive deepening of understanding"; 2) "solution of a driving question that organizes and defines learning needs"; and 3) "production of a series of project artifacts [e.g., reports, presentations, posters] that represent understanding of the driving question." In our High School Enterprise (HSE) program, teams of secondary students work on STEM projects that are authentic and long term, usually spanning multiple academic years. The projects vary from team to team insofar as what the students are actually working on because the students and their teacher-coach select the team's project. A unifying and key focus of our program is that we actively and visibly (to secondary teachers and students) use the engineering design process to frame project work. This makes our program uniquely poised to address many of the issues and obstacles related to promoting STEM awareness and to achieving STEM engagement among secondary students. This paper outlines the aspects of engineering design and of our program implementation that address these issues and obstacles. We cite literature to support our views regarding the benefits of using the engineering design process and provide evidence of benefit from our program assessment. In making these aspects and benefits for secondary education evident, the authors hope to impart to post-secondary educators a broader perspective on the outcomes possible in teaching the process of engineering design.

Introduction

Over the past several years, there has been much concern regarding the global competitiveness of the United States. In 2005, the Gathering Storm Committee put forth several recommended actions to turn around the declining trends in US status, and it gave highest priority to "vastly improving K-12 science and mathematics education."[5] In their 2005 report, the Committee stated that inquiry-based learning (through summer internships and research opportunities) was one of two existing practices it found "attractive" for expansion. Five years later, in 2010, the same committee (minus three former members) issued a follow-up report. They unanimously agreed that the outlook for the United States had worsened and cited that K-12 public education had "shown little sign of improvement, particularly in mathematics and science."[6] These Academies' reports[5-6] and others[7-9] convey an urgency to reform K-12 public education systems. But, changing the US K-12 public school systems (which number over 14,000) presents a great deal of time-consuming inertia to overcome for any change agent. Further, extensive nation-wide curriculum changes ought to be made carefully, with sufficient planning and financial support. In the meantime, as we await needed systemic changes, a broad outreach program such as High School Enterprise can have a much more timely impact.

High School Enterprise (HSE) is an initiative that has established teams of secondary students that work on long-term STEM (science, technology, engineering, and math) projects. The students are guided by STEM teacher-coaches who have been instructed in engineering design, STEM topics, project management, and teamwork. Our pilot study currently has 16 HSE teams that are spread among three states (Michigan, Illinois, and Georgia) and Puerto Rico in various types of secondary schools. A summary of information on the teams and their projects is provided in the Appendix (Table A1), and more information is available at the HSE website (www.highschoolenterprise.org). In a usual HSE implementation, a team of roughly 15 high school students, grades 9-12, is associated with a secondary school and partnered with a local university. The team works on a STEM project that is selected by the team and the coach (a STEM teacher at the high school), and that has local significance for the students and their community. The project continues from one academic year to the next, with most students continuing as well. In the course of their HSE experience, the students solve authentic STEM problems, perform testing and analyses, build prototypes, manufacture parts, stay within budgets, write business plans, and manage their own project. HSE teams also have program-facilitated access to expertise and mentoring from faculty and students in higher education and from professionals in industry. Figure 1 contains a model of the team support offered by the HSE program. Most HSE teams operate as afterschool activities, but we do have in-curricular implementations. When the coaching of an HSE team falls outside of the normal duties of a secondary teacher, the teacher-coach receives a stipend for his/her coaching efforts – just as an athletic coach would. Based on results from our pilot study, we expect that at the conclusion of their HSE experiences students will be prepared to undertake the education/training needed for STEM careers and will be more disposed to select those pathways. In short, the overarching goals of High School Enterprise are to motivate, prepare, and help students to pursue post-secondary STEM education and STEM careers.

The pedagogical premise of High School Enterprise is project-based learning. Although there is some variation in the literature as to what elements of an intervention are required in order for it to be considered "project-based learning,"[1,2] there seem to be some essential components.[3,4] Land and Zembal-Saul[3] have described these (citing Blumenfeld et al.[4]) as follows: 1) "use of long-term investigations that emphasize iterative and progressive deepening of understanding"; 2) "solution of a driving question that organizes and defines learning needs"; and 3) "production of a series of project artifacts [e.g., reports, presentations, posters] that represent understanding of the driving question." At the heart of project-based learning, of course, is the project. In High School Enterprise, the STEM projects that student teams work on are authentic and long term, usually spanning multiple academic years. The project work is framed with the cyclic engineering design process, which provides an iterative venue that facilitates a "progressive deepening of understanding" as students encounter failure and cycle back to prior design steps. The projects vary from team to team insofar as what the students are actually working on because the students and the teacher-coach select the team's project (see Table A1). This aspect of project choice imparts ownership and the "driving question" that fuels project-based learning for each team. Each spring, the secondary HSE teams are brought to the campus of the partnering university to showcase their project work alongside university engineering students at an undergraduate expo event. The HSE teams create posters and presentations (i.e., artifacts) to highlight their project efforts of the academic year. These poster and presentation requirements also promote deeper learning by the formal reflective activities that they entail. They offer opportunities for both coaches and students to assess their progress in terms of the larger picture of a long-term project instead of just day to day gains.

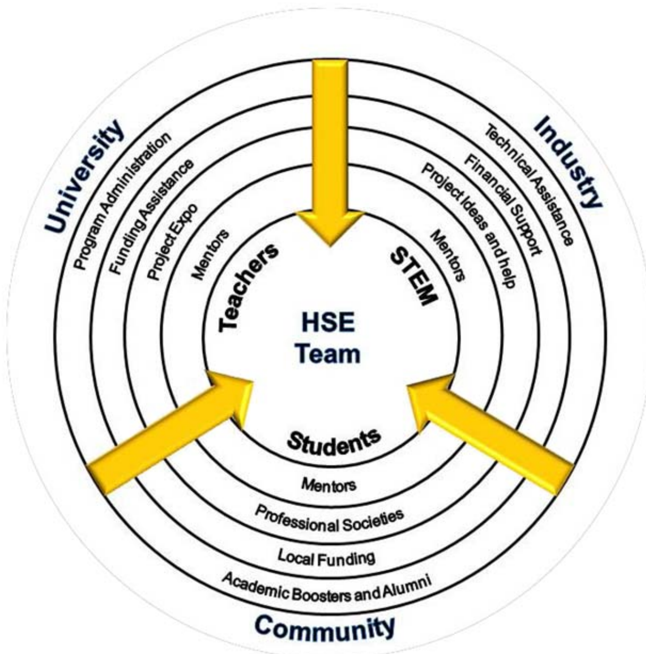

Figure 1. A model of support for the implementation of a High School Enterprise team that shows the student focus of the program and the surrounding support structure that comprises the partnering university, industry partners, and the local community of the host school.

In working on a long-term High School Enterprise project, students are engaged in active, discovery-based STEM learning in a team-based social learning environment. According to educational research, this arrangement (i.e., project-based learning) should be effective at enabling students to learn, understand, and apply STEM content knowledge.[1-4, 10-13] This, in turn, should help prepare them to be successful in pursuit of post-secondary STEM education. But there is more to what project-based learning offers than just cognitive gains – i.e., gains in knowledge of the STEM content areas that are associated with the projects. Metacognitive gains, too, are strongly associated with project-based learning.[1,4,12,14] Metacognition, in simplified terms, generally refers to a person’s self-awareness of and self-regulation of his/her own cognition. And, in simplified terms, cognition can be thought of as the mental processes of knowing or understanding. Educational researchers have linked metacognition to deeper learning and, in particular, to problem solving skills.[14,15] Further, metacognitive skills are associated with the self-regulation part of metacognition,[15] that is, with the ability of the learner to “make adjustments in their own learning processes in response to their perception of feedback regarding their current status of learning.”[17] Metacognitive skills have been described as "higher level thinking"[18] and as the ability of a person to figure out "what to do when you don't know what to do" (Wheatley,[19] as cited by Cooper and Sandi-Urena[16]) – i.e., the ability to problem solve. Effective metacognitive skills must be developed in order to enable self-directed learning.[17] In this last point lies, we believe, the more critical college preparation (because it is a universal need) that High School Enterprise imparts: the enablement of self-directed learning through gains in metacognition, particularly gains in metacognitive skills. In High School Enterprise, these gains are achieved through project-based learning that is structured and framed by the engineering design process – a key aspect of the HSE program.

Benefits of using the Engineering Design Process

A key aspect of High School Enterprise is that we actively, and visibly to the secondary teachers and students, use the engineering design process to frame HSE project work. This helps to unify the support structure for program administrators, and it builds a commonality into the various team projects that facilitates communication among teams and among the teacher-coaches. In order to employ the engineering design process across all projects, we use a fairly general schematic of the design process that was developed by Kampe in previous work for the first-year engineering program at Virginia Tech. The schematic is provided in Figure 2, and it is distributed to all HSE teams as a laminated poster. Though each engineering discipline presents the engineering design process in a manner that is somewhat tailored to the discipline, this general schematic captures most features of prototypical design. In addition to the poster, instruction in engineering design is conveyed to the teacher-coaches during a week-long workshop that they attend each summer. The instruction is a hands-on introduction to the design process and its language, and to several of the basic tools used by engineering design teams. The instruction employs several activities that were initially designed for first-year engineering undergraduates[20] and then expanded for HSE use. The instruction is geared toward novice learners of the design process and conveyed in a manner that facilitates transfer of the instruction to the secondary students.

Use of the engineering design process to frame project work for the secondary students and their coaches offers many benefits that help prepare the high school students for post-secondary STEM education, and these are discussed below. These benefits are also outcomes that can be achieved in the early design education of undergraduate engineering students to enhance their educational experience and their preparation for engineering careers.

1. *An integration of STEM content areas and consequent improvement in science and mathematics education*
   In the recently released report *Successful K-12 STEM Education*,[10] teaching engineering design in K-12 was noted as a way to integrate STEM subjects and "provide opportunities for making STEM learning more concrete and relevant." In the 2009 report *Engineering in K-12 Education*,[21] the authoring committee cited evidence that science and mathematics education were improved by placing engineering education in K-12 classrooms. They found this particularly compelling in light of two Department of Education publications that reported 1) little progress in attaining the science and math education goals set in 1990[22] and 2) the lack of hard evidence on effectiveness of the federally funded programs with a math or science focus.[23] In *Engineering in K-12 Education*, the committee noted further that "engineering design has the potential to

narrow achievement gaps," citing the work of Akins and Burghardt.[24] In their work, much more pronounced improvements in math and science scores were observed for 7th-9th grade students who were in the bottom two quartiles on pre-treatment scores. Further, in the newly released framework document for the impending revisions of national standards for K-12 science education, the authoring committee states as follows: "Defining and solving the problem, that is, specifying what is needed and designing a solution for it, are the parts of engineering on which we focus in this framework, both because they provide students a place to practice the application of their understanding of science and because the design process is an important way for K-12 students to develop an understanding of engineering as a discipline and as a possible career path."[25]

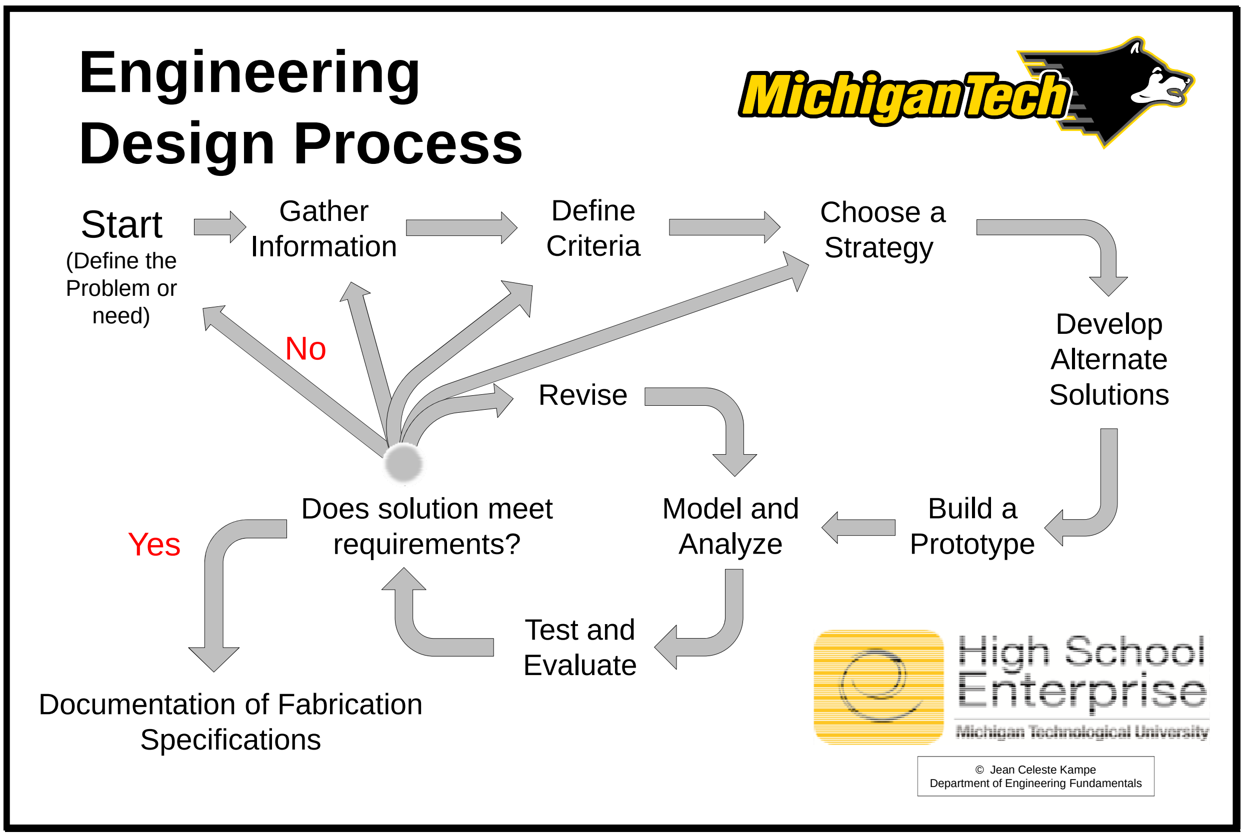

Figure 2. The engineering design process as it is presented to the secondary teacher-coaches and students participating in High School Enterprise. This model of the design process was developed by Kampe in previous work. A laminated poster (24x36 inches) of this figure is provided to each HSE team.

2. *A scaffolding framework for teaching/imparting metacognitive skills*
In order to avail the potential of project work to improve student learning, particularly through metacognitive gains, the teacher functions as a coach or guide who facilitates the students' learning processes through scaffolding, that is, by providing interventions that

build metacognitive skills.[2,26-29] The engineering design process (see Figure 2) provides an overarching map or guide for such scaffolding that can help HSE teacher-coaches understand the type of intervention to provide for a team's current place in the process. In putting such a map in the students' sight (literally, through the design process posters) and visibly using it to strategize about the "next step," teacher-coaches move their teams toward ownership of their learning and self-direction. Further, working on open-ended HSE projects with the engineering design process helps teachers improve their own metacognitive functioning, and that improves their ability to provide effective scaffolding for student gains in metacognitive skills.

3. *An authentic venue for the cyclic practice of convergent and divergent thinking*
   Due to the open-endedness of design problems, engineering design offers an inquiry-based venue that by necessity employs both convergent and divergent thinking. From an overall perspective, this is seen in the cyclic nature of the design process as it is presented in Figure 2. Any need to return to "prior steps" in the upper portion of the figure is surely a trek into the conceptual domain of divergent thinking. Clockwise travel in the cycle (without return to prior steps) is a convergent process that falls in the knowledge domain. But, the iteration of divergent and convergent thinking that is "design thinking"[30,31] should occur at all stages of the design process because answers to design questions at any point in the process ought to be flexible[30] and carry conceptual input. Practicing both convergent and divergent thinking is important to critical thinking, and both are used in problem solving.[32] Traditional education in math and the sciences, and in a good part of fundamental engineering, focuses on scientific methods that use convergent thinking to get to the single-solution answers of closed-ended problems.[31] Creativity and innovation, however, require divergent thinking *and* the metacognitive skills to manage it. So, in using engineering design to frame project work, High School Enterprise offers a vehicle both to instill the practice of divergent thinking in secondary students and to develop the metacognitive skills to use that practice effectively.

4. *A clear message about the value of diversity*
   In attempts to increase the numbers of underrepresented minority students in higher education, the argument for affirmative action processes has moved from remediation (to amend past wrongs) to one of diversity for enhancing the learning environment. Neither remediation nor diversity for its own sake seems likely to be an attractive reason to participate in higher education from the perspective of an underrepresented minority student. An understanding of the engineering design process, however, offers a clear and compelling message to all students on the value of, and the need for, participation of underrepresented peoples in STEM fields, especially in engineering. In the decision making procedures that are built into the design process through common tools that design teams use (constraints, criteria/objectives, metrics to evaluate alternative designs, and decision matrices), only the voices of those present on the design team are heard. That means that the insights and true needs of those not present are either unavailable to, or potentially misunderstood by, the design team, and the solution suffers from that lack of input. One of the first voices along this line of thinking came from Dr. William A. Wulf (University of Virginia) in the latter half of the 1990s during several of his first addresses as president of the National Academy of Engineering.[33] If this situation is

clearly and actively demonstrated to secondary teachers in such a way that they can understand it and easily carry that understanding back to their students, then the message conveyed for underrepresented participation becomes an honest and emphatic "We need you!" This is the approach of High School Enterprise. We use a decision matrix activity developed for first-year engineering undergraduates that compares staple remover designs.[20] Within the exercise, the outcome of the decision matrix is shown to be dependent on the criteria used and the weighting of those criteria – both of which are established by the design team. From there, it is a clear conclusion that the outcome of the matrix (a design decision-making tool) is impacted only by voices on the design team, and we have effectively conveyed that more powerful "We need you!" message through this exercise.

5. *A safe avenue to experience failure, to learn from it, and a way to thusly empower underrepresented students to persist in STEM pursuits*
   An important aspect of HSE is the longevity of the team projects. All HSE teams work on a project for at least one full academic year, and that is a substantial length of time for a high school project. For many teams, project work continues for multiple academic years. Of the 16 host schools listed in Table A1, 10 teams are continuing HSE project work from the previous academic year, and 6 of those from the year prior. Such project longevity is a key factor in truly engaging students in real-world STEM applications, and it carries the inherent benefit of providing the time needed for students to fact find and to establish a deep research approach to the project. These are two aspects of problem solving that have been described as "vital stages in the creative process."[34] Long-term efforts on a continuing project also offer the opportunity for students to fail, often, in their design attempts to solve a STEM-based problem and to try anew, again, learning with each attempt. Frequent failure has been strongly linked to creativity and innovativeness in the workplace and, ultimately, to very successful people.[35] Traditional education is not geared toward failure. High School Enterprise, by virtue of its emphasis on the cyclic engineering design process, *is* geared toward failure – failure as an expected and structured pathway to success in problem solving. In other words, a safe opportunity to struggle, to fail, and to try again and again is afforded by framing the long-term STEM projects used in HSE with the cyclic engineering design process. In accord with the research of Carol Dweck that is profiled in the recent AAUW publication *Why So Few?*,[36] this arrangement provides further benefits by promoting a "growth mindset" in student participants. It demonstrates to them that they can learn the skills needed to be successful problem solvers, and that failure and struggling are expected, acceptable, and enjoyable ways of learning. Dweck's work indicates that such a "growth mindset" may help underrepresented participants survive the negative impact of stereotype and bias that they will likely encounter in their STEM pursuits.[37] Indeed, in the executive summary of *Why So Few?*, social and environmental factors were cited as still being contributors to the underrepresentation of women in STEM fields.[36]

6. *A vehicle to improve the technological literacy of secondary teachers and students*
   In the 2002 report *Technically Speaking: Why All Americans Need to Know More about Technology*, the authoring committee presented the characteristics of technologically literate people; under the category of knowledge, they listed "is familiar with the nature

and limitations of the engineering design process."[38] High School Enterprise teaches the engineering design process to the STEM teacher-coaches through hands-on activities at summer workshops, and they carry the process to their students. The HSE project work is framed with the design process, so the HSE teams use engineering design on a regular basis throughout their project work. From our pilot study and what we witness of HSE student work at Expo, this approach leads to an understanding of the engineering process by the participating students and the teacher-coaches. Further, in first-hand use of the process, and from the message on the value of diverse design teams (#4 above), the limits of the design process become evident.

Evidence of benefits

For evidence of realizing the benefits enumerated above, we looked first for evidence of the engineering design process being understood by the secondary teachers and being carried to their students. The instruction of design occurs in a week-long summer workshop that all HSE teacher-coaches attend, whether they are novice HSE participants who will embark on coaching a team in the subsequent academic year, or whether they are veteran teacher-coaches anticipating their next year of HSE involvement. Following each workshop session, the teachers are asked to assess the given session using an online survey tool. Table 2 contains design sessions results for survey questions that relate to the level of the instruction and the usefulness of the design content. These results are for the three formal workshops that have occurred (summers of 2009, 2010, and 2011). Within Table 2, there are two design sessions listed. The introduction session centers on the decision matrix activity mentioned earlier, and it emphasizes the value of diversity. The advanced design session centers on morphological charts and design space, and it uses a team-based toaster take-apart exercise. Both sessions convey the language of design and instruction on general design tools. The introduction session is delivered to novice HSE teacher-coaches. The advanced session is delivered to veteran coaches and it teams more experienced coaches with those having less HSE experience. Which session is offered during the workshop depends on the level of HSE experience of the teachers, who were almost all novices in 2009 and veterans in 2011. These assessment results (Table 2) indicate that design process instruction is adequately conveyed and that it is conveyed in a manner that allows the secondary teachers to believe that they will be able to use the instruction/content with their HSE team.

Evidence that the HSE teams do, in fact, apply the engineering design process is clear in the artifacts that the teams generate for each spring Expo. The team posters and presentations on their projects often use design language (correctly) and sometimes incorporate design tools (e.g., a decision matrix). Further evidence of process use by secondary HSE student teams has been presented in an earlier (2010) DEED paper.[39] Demonstrated competent use of the design process in long-term project work by the secondary students seems to us to be sufficient evidence that the first three benefits outlined above (integration of STEM content areas, provision of a scaffolding framework for gains in metacognitive skills, provision of an authentic venue for cyclic convergent/divergent thinking) are imparted to HSE participants – at least to some extent. Comments from teacher-coaches on the engagement of their students with the project work and with learning support our contentions. In fact, one teacher-coach has reported that, in the course of their project work, the students have questioned the presented order of the design process (see Figure 2). They had mistaken the "Choose a Strategy" step (used to reduce the number of design options when a project's design space becomes unwieldy) for their decision matrix step (used to select which candidate design, from among the alternate solutions, to advance to prototype). This questioning, to us, is a strong indicator of the students' use of the design process.

With specific regard to process use by the secondary teachers, one has used the design process schematic by Kampe in a recent publication on remotely operated vehicles (ROVs) in the classroom. Another HSE teacher-coach, who was recently appointed as principal of her school, plans to implement the engineering design process with her faculty to revise their curriculum. The teachers also make many requests for additional Figure 2 posters – to replace copies lost during summer classroom cleanings, to post in additional classrooms, and to share with other teachers.

Table 2. Summer workshop design sessions assessment results for survey items linked to level of instruction and usefulness of content.

Summer Workshop Year		2009	2010		2011
Design Session		Introduction	Introduction	Advanced	Advanced
Number of respondents		9	8	9	20
Survey Item	Response Options	Percentages (Number of responses)			
Usefulness of the topic	Excellent	66.7% (6)	100% (8)	88.9% (8)	70.0% 14)
	Good	22.2% (2)	0.0% (0)	11.1% (1)	30.0% (6)
	Fair	11.1% (1)	0.0% (0)	0.0% (0)	0.0% (0)
	Poor	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
	N/A	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
Usefulness of the resources	Excellent	55.6% (5)	100% (8)	88.9% (8)	80.0% (16)
	Good	44.4% (4)	0.0% (0)	11.1% (1)	20.0% (4)
	Fair	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
	Poor	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
	N/A	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
Amount of information	Excellent	44.4% (4)	100% (8)	77.8% (7)	70.0% (14)
	Good	33.3% (3)	0.0% (0)	22.2% (2)	25.0% (5)
	Fair	11.1% (1)	0.0% (0)	0.0% (0)	5.0% (1)
	Poor	11.1% (1)	0.0% (0)	0.0% (0)	0.0% (0)
	N/A	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
Clarity of communication	Excellent	66.7% (6)	100% (8)	100% (9)	80.0% (16)
	Good	22.2% (2)	0.0% (0)	0.0% (0)	20.0% (4)
	Fair	11.1% (1)	0.0% (0)	0.0% (0)	0.0% (0)
	Poor	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
	N/A	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
Pace of delivery	Excellent	66.7% (6)	100% (8)	87.5% (7)	85.0% (17)
	Good	33.3% (3)	0.0% (0)	12.5% (1)	10.0% (2)
	Fair	0.0% (0)	0.0% (0)	0.0% (0)	5.0% (1)
	Poor	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
	N/A	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
What is the likelihood of you using this material for your HSE team?	Definitely will use:	55.6% (5)	100% (8)	77.8% (7)	65.0% (13)
	Probably will use:	33.3% (3)	0.0% (0)	22.2% (2)	25.0% (5)
	Might use:	11.1% (1)	0.0% (0)	0.0% (1)	10.0% (2)
	Will not use:	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)

In moving to a discussion on the evidence of conveying a stronger diversity message through design, a background on the breadth of the High School Enterprise program is helpful. Information on teams, coaches, projects, and host locations for current HSE implementations is provided in Table A1 of the Appendix. A summary of school locales and profiles is provided in Table 3 below, and a summary of student/teacher participant numbers is provided in Table 4. HSE serves a large number of minority and female students, though the ethnic diversity of any given team is usually low. This is not surprising as primary and secondary schools are among the most segregated institutions. HSE, however, is a sufficiently flexible program to adapt to a mode that works best in the host institution and serves the students as the educators of the school see fit. This is evident in the various types of HSE hosts. There are alternative high schools (institutions that often serve as a last resort in public education), magnet schools, technical schools, charter schools, traditional public high schools, as well as schools that also employ Project Lead the Way (PLTW) or FIRST Robotics. HSE is flexible enough to facilitate other STEM programs (e.g., PLTW and FIRST Robotics) and to work in highly structured institutions such as magnet and technical high schools. Yet, HSE is also structured enough to offer true implementation assistance to schools or programs that may lack the resources to establish a formal project-based STEM learning initiative on their own (e.g., alternative high schools or inner city schools). The schools involved with HSE are diverse in locale (rural, suburban, inner city) and in the characteristics of the students they serve (all income ranges, high populations of students from underrepresented groups). Among the host schools are thirteen Title I schools and, in nine of those, Title I is a school-wide program (i.e., 40% or more of students served by the institutions are from low-income families). Variations among the school types and school districts lead to differences in how HSE implementation evolves at these schools, and the differences are likely required in order to produce successful and sustainable implementations. The flexibility of the HSE program to be implemented in the best manner for the host school is a strength of the program. Further, a notable aspect of the HSE program is that there are no participation prerequisites (academic or otherwise) imposed on students by the High School Enterprise program; a willingness to participate and project interest are the deciding factors. Student participation in HSE is purely voluntary. Though there are in-curricular instances of HSE teams, the existence (or not) of prerequisites for course participation is a decision of the educators at the host school, and all of these in-curricular HSE implementations are associated with elective courses.

The total percentage of minority students participating in HSE (the sum of African American, Hispanic, and "other" minority students as listed in Table 4) has grown from 39 to over 60% for average participation numbers of over 200 students. Among the ethnic minority groups that HSE students report, African American is reported in the highest number. In fact, for the current academic year, over 50% of HSE student participants have self-identified as African American. Female participation has been relatively steady at around 35%. An additional important demographic result to report is that of diversity among the teacher-coaches. Although women are underrepresented in STEM, currently five of the HSE teacher-coaches are women and four of them are from minority groups. Having diverse role models is also an important factor in motivating diverse students to pursue STEM education and careers. Maintaining the diversity of teacher-coaches is an ongoing objective of the HSE program.

Table 3. Profiles of current (AY2011-12) host schools participating in the High School Enterprise program.

High School and Location	Rural	Urban	Title I*	High Minority	At Risk
1. Arthur Hill H.S., Saginaw, MI		X	XX	X	X
2. Benjamin E. Mays H.S. Atlanta, GA		X	XX	X	X
3. B.R.I.D.G.E. Alternative H.S., Hancock, MI	X		X		X
4. Cass Tech H.S., Detroit, MI		X	XX	X	X
5. Chassell H.S., Chassell, MI	X		X		
6. Dollar Bay H.S., Dollar Bay, MI	X		X		
7. Hancock, H.S., Hancock, MI	X		X		
8. Horizons Alternative H.S., Calumet, MI	X		XX		X
9. Manuel A. Toro Morice H.S., Puerto Rico		X	XX	X	X
10. Melvindale H.S., Melvindale, MI		X	XX	X	X
11. Oak Park High School, Oak Park, MI		X	XX	X	X
12. Tech High, Atlanta, GA		X	XX	X	X
13. Traverse City H.S., Traverse City, MI					
14. University of Chicago Woodlawn Charter H.S., Chicago, IL		X	XX	X	
15. University Prep H.S., Detroit, MI		X	X	X	X
16. Utica Community Schools, Utica, MI			X		

* X indicates a Title I school and XX indicates that Title I is a school-wide program.

Table 4. A summary of High School Enterprise participants for the three most recent years of implementation. Details on the AY2011-12 implementation are found in Table A1.

HSE Implementation Year	**AY2009-10**	**AY2010-11**	**AY2011-12**
Number of host sites	12	16	16
Number of sites continuing from prior year of NSF ITEST implementation	n/a	11	15
Students:			
Total number of students	173	286	207
Average number of students per team	14	18	13
Number of female students	66 (38%)	99 (35%)	70 (34%)
Number of African American students	39 (23%)	107 (37%)	109 (53%)
Number of Hispanic students	23 (13%)	34 (12%)	16 (8%)
Number of “other” minorities	6 (3%)	13 (5%)	1 (0.5%)
Teachers:			
Total	13	17	18
Number of STEM teachers	12	16	16
Number of female teachers	3	5	5
Number of ethnic minority teachers	2 (1 female)	4 (3 female)	6 (4 female)

To provide evidence of the safe failure avenue that the engineering design process provides and its benefits, we examined excerpts from two on-line chats among the HSE teacher-coaches. The chats were captured during on-line biweekly HSE meetings conducted by our HSE program implementation director, Oppliger. Teachers responded to prompts from Oppliger that asked how their students learn from failure and at what point do they, as coaches, step in to avoid it (20 Oct 2010), and how the HSE learning environment differs from their typical school-day environment (10 Nov 2010). The complete lists of responses to these prompts are provided in the Appendix (see On-Line Chat Excerpts). Here we present several relevant comments, with typing errors preserved:

“The student rushed to wire up the controls of the ROV. It was explained to the student how to wire it up and he thought he understood it perfectly. However, he wired it up incorrectly and like most men they blamed every other system except his wiring. He learned that troubleshooting was an important tool in the Engineering design process.”

“failure is the real learning process because students must learn and develop from failure to go forward. Edison knew over 2000 ways of how not to make a light-bulb”

“It also depends on how expensive the failure is. One of then nice things about school or enterprise is the failure here is 'safe'.”

“I preach that failure is not an option, that if they get stuck they need to brainstorm around the issue and that might be phone calls between me and the students in the evening coming up with some solutions, since idea’s don’t just pop into our heads during our 50 minute class.”

“It also is difficult to get student [to] continue after failure. If the idea does not work or the student is wrong, they are used to, in the classroom setting, having the solution or correct [answer] given instantly.”

“Project based learning is fundamentally interdisciplinary and should go beyond STEM (eg. English, SS, History, Arts)”

“Cross Curricular, not based on academics or athletic ability”; “greater diversity”

“student driven, research based, deep problem solving component”

“Only class with 9th - 12th graders, choice in what they want to be graded on, team oriented, freedom to create and design, student led, long term, lecture series from STEM professions, lots of field trips”

“Not assessed in traditional ways: The syllabus has 19% of grade to communication, other areas assessed are teamwork, creativity, and management”

“Students are ENCOURAGED to fail...,” “Exposure to work from Georgia Tech (Mat Sci lesson and polymers lesson) and MTU (decison matrix and cyclic model from Kampe)”

To gather evidence of students’ and teachers’ improved technical literacy, we looked to our spring Expo. For student HSE participants, the annual spring campus visit for the event serves many purposes. It allows face-to-face interaction among students from different teams, which expands the HSE peer-support network for students beyond just in-house team members. It offers an opportunity for the secondary students to interact with upper-class undergraduate students who are presenting their work in the same venue, and gives the high school students a first-hand look at college-level student efforts. The Expo serves as the venue for formal presentation of HSE project work. The secondary students design and create posters to showcase their project work, and they are required to give oral presentations to an audience that comprises HSE teams and teacher-coaches, university faculty, and undergraduate engineering students who serve as presentation judges. A member of the external evaluation team for the HSE program also scores the presentations and posters of the secondary students.

Deeper learning is promoted by the formal reflective activities built into the HSE program through these poster and presentation requirements because these activities promote metacognitive gains. They offer opportunities for both coaches and students to assess their progress in terms of the larger picture of a long-term project instead of just day to day gains; that is, they impose divergent thinking. Additionally, the Expo campus visit has the critically important function of making the university accessible to the secondary students.

From the artifacts created for spring Expo, we see trends toward an improved ability of students to communicate technical information and an improved understanding of the design process with continued HSE participation and continued use of the process. At Expo, the artifacts created by the students are scored by an external evaluator for content and manner of presentation. Results, for the past three years, of this formative assessment are presented in Tables 5A (team presentations) and 5B (team posters). To organize these results, the schools have been categorized into cohorts as determined by their participation levels as HSE host institutions: Cohort I schools began hosting an HSE team in the 2008-09 academic year (AY2008-09) or before, Cohort II schools began in AY2009-10, and Cohort III in AY2010-11. In Tables 5A and 5B, the results are then clustered further (boxed) by the number of times the schools had presented at Expo. This clustering has been done to bring into evidence the benefit that continued participation *of the school* in the HSE program has on the quality of the artifacts created for Expo. It should be noted, however, that a school's cohort number does not necessarily reflect the HSE participation level of students on the school's team. HSE participation is voluntary in all instances and, in most after-school implementations of HSE teams, new students may join at the start of each academic year. Student attrition at the end of each academic year is also possible. So at the end of AY2010-11, although a Cohort I school had hosted an afterschool HSE team for at least three years and presented at Expo three times, the students on the AY2010-11 team for that school were likely a mix of students with one, two, or three years of HSE participation. For in-curricular HSE implementations that are accomplished through elective courses, each academic year brings a fully new group of students to the school's team. All students on a Cohort I school team with this type of HSE implementation would have only one year of HSE experience at the end of AY2010-11, though the school had presented three times at Expo. The HSE participation level of the teams' teacher-coaches also impacts the quality of student-produced artifacts. A veteran Cohort I coach, with refined scaffolding interventions at his/her disposal, could have better guided a team of all new students in AY2010-11 than, perhaps, a Cohort III (new) coach could have guided his/her team of new students.

Summary

High School Enterprise has demonstrated that project-based learning which is framed by the engineering design process imparts benefits to high school student learning that go beyond cognitive gains. It is expected that similar benefits could be realized in the early education of undergraduate engineering students through the use of long-term projects that are framed with the engineering design process.

Table 5A. Team Presentations Assessment Results. External evaluator scores on oral team presentations were generated using a rubric with seven scoring categories for a possible total score of 35 points; (two projects did not include all scoring categories, thus a total score of 20 was possible). Scores are from spring expos in 2009, 2010, and 2011. Cohort I schools participated in all three expos, Cohort II schools in Expos 2010 and 2011, and Cohort III schools in Expo 2011 only. Although schools are categorized by cohort, the students on the respective teams may have differing and/or mixed levels of HSE participation.

<u>Schools' First-Year Expo Presentation Scores</u>:

Cohort I Schools in Expo 2009

Total score out of 35 possible points	-	17	22	27	30	Average of 35-point presentation scores : 24.00
Total score out of 20* possible points	11	-	-	-	-	
Projects (n = 5)	1	1	1	1	1	

*Three categories were not pertinent to this project because of the nature of the presentation (no PowerPoint).

Cohort II Schools in Expo 2010

Total score out of 35 possible points	12	19	21	23	26	31	Average of 35-point presentation scores: 22.00
Projects (n = 6)	1	1	1	1	1	1	

Cohort III Schools in Expo 2011

Total score out of 35 possible points	23	24	25	Average of 35-point presentation scores: 24.00
Projects (n = 3*)	1	1	1	

*One other project could not be observed because presentations were held concurrently.

<u>Schools' Second-Year Expo Presentation Scores</u>:

Cohort I Schools in Expo 2010

Total score out of 35 possible points	26	27	29	Average of 35-point presentation scores: 27.25
Projects (n = 4)	1	2	1	

Cohort II Schools in Expo 2011

Total score out of 35 possible points	-	21	25	31	Average of 35-point presentation scores: 25.66
Total score out of 20* possible points	14	-	-	-	
Projects (n = 4**)	1	1	1	1	

*Three categories were not pertinent to this project because of the nature of the presentation (no PowerPoint).
**One other project could not be observed because presentations were held concurrently.

<u>Schools' Third-Year Expo Presentation Scores</u>:

Cohort I Schools in Expo 2011

Total score out of 35 possible points	27	31	Average of 35-point presentation scores: 29.00
Projects (n = 2*)	1	1	

*Two other projects could not be observed because presentations were held concurrently.

Table 5B. Team Posters Assessment Results. External evaluator scores for project posters were generated using a rubric with six scoring categories for a possible total score of 30 points. Not all teams displayed a poster. Scores are from spring expos in 2009, 2010, and 2011. Cohort I schools participated in all three expos, Cohort II schools in Expos 2010 and 2011, and Cohort III schools in Expo 2011 only. Although schools are categorized by cohort, the students on the respective teams may have differing and/or mixed levels of HSE participation.

Schools' First-Year Expo Poster Scores:

Cohort I Schools in Expo 2009

Total score out of 30 possible points	20	22	24	25	Average of total scores: 22.75
Projects (n = 4)	1	1	1	1	

Cohort II Schools in Expo 2010

Total score out of 30 possible points	8	18	20	22	27	Average of total scores: 19.17
Projects (n = 6)	1	1	2	1	1	

Cohort III Schools in Expo 2011

Total score out of 30 possible points	19	20	29	Average of total scores: 21.75
Projects (n = 4)	2	1	1	

Schools' Second-Year Expo Poster Scores:

Cohort I Schools in Expo 2010

Total score out of 30 possible points	23	28	29	Average of total scores: 25.75
Projects (n = 4)	2	1	1	

Cohort II Schools in Expo 2011

Total score out of 30 possible points	18	20	26	28	Average of total scores: 22.40
Projects (n = 5)	1	2	1	1	

Schools' Third-Year Expo Poster Scores:

Cohort I Schools in Expo 2011

Total score out of 30 possible points	23	24	29	Average of total scores: 24.75
Projects (n = 4)	2	1	1	

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Appendix

On-Line Chat Excerpts: Chats among High School Enterprise teacher-coaches are captured during biweekly Adobe Connect meetings. Excerpts below are the complete list of responses from the teachers for prompts that were provided by Oppliger (underlined).

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<u>Prompt from on-line meeting 20 OCT 2010</u>: How do students learn from "failure" or from when things don't go "according to plan"? Examples?

Alan Gravitt: I have heard that You have not failed until you give up trying

Geoff Clark: The student rushed to wire up the controls of the ROV. It was explained to the student how to wire it up and he thought he understood it perfectly. However, he wired it up incorrectly and like most men they blamed every other system except his wiring. He learned that troubleshooting was an important tool in the Engineering design process.

Matt Zimmer: Part of our role is getting students to not instantly blame others or the coach

Alan Gravitt: Has anyone seen the frog and stork cartoon , never never never give up with the half swallowed frog choking the stork to prevent final oblivion

<u>Oppliger</u>: At what point do you step in to avoid failure? tough question. We certainly don't want anyone to get physically hurt ... but we don't want to protect students completely either.

Bill Grimm: failure is the real learning process because students must learn and develop from failure to go forward. Edison knew over 2000 ways of how not to make a light-bulb

Matt Zimmer: It also depends on how expensive the failure is. One of then nice things about school or enterprise is the failure here is ''safe''.

Geoff Clark: I preach that failure is not an option, that if they get stuck they need to brainstorm around the issue and that might be phone calls between me and the students in the evening coming up with some solutions, since idea’s don’t just pop into our heads during our 50 minute class.

Alan Gravitt: In general , science would expect that the experiment that fails to support the hypothesis is not a failure but opens the door to the next better hypothesis that is supported

Keith in TC: As a coach you have to recognize frustration and try to redirect a students efforts

Matt Zimmer: It also is difficult to get student continue after failure. If the idea does not work or the student is wrong, they are used to, in the classroom setting, having the solution or correct given instantly.

****

Prompt from on-line meeting 10 NOV 2010: How is the HSE learning environment different from that of the typical school-day?

Rajdl and Smith: Project based learning is fundamentally interdisciplinary and should go beyond STEM (eg. English, SS, History, Arts)

Celeste: Cross Curricular, not based on academics or athletic ability
Celeste: greater diversity

Author: [from Randy Thomas who was only on the phone] - student driven, research based, deep problem solving component

Matt Zimmer: Many of our students are learning to work and speak with professionals and businesses in the community.

Assata, UCW: Only class with 9th - 12th graders, choice in what they want to be graded on, team oriented, freedom to create and design, student led, long term, lecture series from STEM professions, lots of field trips,

Oppliger: From Randy - students set own weekly goals and objectives. These are reviewed at end of week to plan for the future accordingly.

Keith in TC: Forces students to be more resourceful

Mary Markham: leadership skills.... some of the students who are not usually ''in Charge'' end up being in charge.

Matt Zimmer: How to manage a budget and find work-arounds when traditional methods are cost prohibitive.

Assata, UCW: Not assessed in traditional ways: The syllabus has 19% of grade to communication, other areas assessed are teamwork, creativity, and management
Assata, UCW: Students are ENCOURAGED to fail...
Assata, UCW: Exposure to work from Georgia Tech (Mat Sci lesson and polymers lesson) and MTU (decison matrix and cyclic model from Kampe)

Keith in TC: Does this include time put in by coaches outside of when students meet?

****

Table A1. High School Enterprise (HSE) team/project details and 16 host schools for the 2011-12 academic year.

	High School and Location	Coach: Content Area	Team Makeup	Project Description	University Partner & Funding Sources
1	**Arthur Hill High School** large urban city Saginaw, MI 48602	Celeste Conflitti: Biology, Environmental Science	Number of Students: 12 Minority: 12 Women: 6 Grades: 11	DIPLOMATS: Redesign and development of green space on school grounds.	Michigan Tech & NSF-ITEST
2	**Benjamin Mays High School** large urban city Atlanta, GA 30326	Geraldine Nix: Engineering (retired) Ricardo Jones: Science, Engineering	Number of Students: 7 Minority: 7 Women: 3 Grades: 9-12	Aquaponics for growing food in an urban environment	Georgia Tech & NSF-ITEST
3	**B.R.I.D.G.E. Alternative High School** small semi-rural city Hancock, MI 49930	Chuck Palosaari: General Science, Math	Number of Students: 4 Minority: 0 Women: 2 Grades: 9-12	Team is examining project possibilities with environmental emphasis (e.g., planning and construction of a walking trail or observation tower on property of a project partner)	Michigan Tech & Lake Superior Stewardship Initiative, NSF-ITEST
4	**Cass Technical High School** large urban city Detroit, Michigan 48201	Ernestine Smith: Business Technology (retired) Kelly Patterson: Business Technology	Number of Students: 10 Minority: 10 Women: 3 Grades: 9-12	IYM (Innovative young Minds): Development of graphics-rich STEM teaching material for elementary grades. First project focuses on solar energy. Products will be paper (books) and digital (video and video game)	Michigan Tech & NSF-ITEST
5	**Chassell High School** rural town/village Chassell, MI 49916	Mary Markham: Science, Chemistry, Math	Number of Students: 4 Minority: 0 Women: 0 Grades: 11	INANO: Integrate Vernier sensors and LabVIEW software into LEGO NXT model of an AFM microscope which was constructed in the first HSE year.	Michigan Tech & Michigan Tech, NSF-ITEST

Table A1 continued.

6	**Dollar Bay High School** rural town/village Dollar Bay, MI 49922	Matt Zimmer: Math, Science, Technology & Design	Number of Students: 21 Minority: 0 Women: 6 Grades: 9-12	SOAR (Student Organization for Aquatic Robotics): ROV engineering and exploration of local marine environments	Michigan Tech & Lake Superior Stewardship, Michigan Tech, NSF-ITEST
7	**Hancock High School** small semi-rural city Hancock, MI 49930	Brian Rajdl: Physical & Environmental Science Stephen Smith: Language Arts	Number of Students: 12 Minority: 0 Women: 3 Grades: 11-12	PEAK (Partnering the Environment and Academics in the Keweenaw) Study and map the Swedetown Creek area. Stream monitoring and water chemistry. GPS/GIS technologies. Stream Gauging. Land Use and Riparian Protection.	Michigan Tech & NSF-ITEST
8	**Horizons Alternative High School** small semi-rural city Mohawk, MI 49950	Lucas Theisen: Language Arts	Number of Students: 7 Minority: 0 Women: 1 Grades: 10-12	Using Google SketchUp to help design an underwater ROV. Build the ROV for a specific purpose. Test and use the ROV in spring 2012	Michigan Tech & NSF-ITEST
9	**Manuel A. Toro Morice School** large urban city Caguas, PR 00725	Juan Serrano Osorio: Mathematics	Number of Students: 14 Minority: 14 (Latin/Latino) Women: 8 Grades: 10-12	Design and fabrication of a human and electrically powered light commuting vehicle.	Universidad del Turabo & NSF-ITEST
10	**Melvindale High School** large urban city Melvindale, MI 48122	Randy Thomas: Physics, Chemistry	Number of Students: 12 Minority: 6 Women: 5 Grades: 9-12	Cyber Cards: redesign of electric vehicle using sustainable/renewable fuel sources.	Michigan Tech & NSF-ITEST, Square One Education Network

Table A1 continued.

11	**Oak Park High School** large urban city Oak Park, MI 48237	Bill Grimm: Physics, Physical Science	Number of Students: 29 Minority: 29 Women: 9 Grades: 9-10	Wireless Technology and Cell Phone Applications	Michigan Tech & Square One Education Network, Michigan Tech, NSF-ITEST
12	**Tech High School** large urban city Atlanta, GA 30316	Hien Luong: Physics, Engineering	Number of Students: 10 Minority: 10 Women: 3 Grades: 11	Develop a design and prototype for a school locker system that uses a card-swipe reader for access	Georgia Tech & NSF-ITEST
13	**Traverse City Central H.S.** mid-sized city Traverse City, MI 49686	Keith Forton: Physics	Number of Students: 13 Minority: 0 Women: 3 Grades: 9-12	Design and build underwater ROVs and use ROV technologies to study the marine environment in the Traverse City area.	Michigan Tech & NSF-ITEST
14	**University of Chicago Woodlawn Charter H.S.** large urban city Chicago, IL 60637	LaMailede (Assata) Moore: Engineering	Number of Students: 25 Minority: 25 Women: 10 Grades: 9-12	Students will study and research seismology by building an earthquake table and researching the effects of fault slippage on the region near Haiti.	Michigan Tech, & Self-Funded
15	**University Prep Math Science H. S.** large urban city Detroit, Michigan 48201	Nicholas Fell: Engineering - PLTW	Number of Students: 13 Minority: 13 Women: 6 Grade: 9&10	Convert a battery power child-size jeep into an autonomous navigating vehicle.	Michigan Tech & NSF-ITEST, IBM Corp.
16	**Utica Community Schools** suburban city Utica, MI 48317	Geoffrey Clark: Engineering Technology	Number of Students: 12 Minority: 0 Women: 2 Grades: 10-12	Design and implement a small scale, in-school aquaponics system and monitor its functioning.	Michigan Tech & NSF-ITEST