Introducing High School Students to Engineering Fundamentals by Four Weeks Engineering Innovation Summer Program

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Abstract: Preparing high school students for engineering disciplines is crucial for the sustainable scientific and technological developments in the USA. This paper discusses a precollege program, which not only exposes students to various engineering disciplines but also enables them to consider engineering as their profession. The four-week long "Engineering Innovation (EI)" course is offered every year to high school students by the Center for Educational Outreach, Whiting School of Engineering, Johns Hopkins University. The EI program is designed to develop problem-solving skills through extensive hands on engineering experiments and projects. A team consisting of an instructor, generally a PhD in Engineering, and a teaching fellow, generally a high school science teacher, closely work with students to pedagogically inculcate basics of core engineering disciplines such as civil, mechanical, electrical, materials, and chemical engineering. EI values independent problem-solving skills and simultaneously promotes team spirit among students. A number of crucial engineering aspects such as professional ethics, communication, technical writing, and understanding of common engineering principles are instilled in high school students via well-designed individual and group activities. This paper discusses the model of the EI program and its impact on students learning and their preparation for the engineering career.

Introduction: Shortage of engineering students threatens US's role as world's leading innovator.[1] According to CNN news unprepared college students entering in science, engineering, and mathematics drop out after their first year itself. The alarming percentage of dropout is around 20%.[2] Engineering workforce in American industries will need an unprecedented number of engineers in near future to remain competitive and to advance cutting-edge scientific development.[1] To produce a large number of highly skilled engineering graduates it is crucial to make the high school students interested and prepared in the engineering disciplines.[1,3] Early exposure of engineering disciplines provides unique opportunity for the high school students to evaluate engineering profession as a future career.[4] In addition to early engineering exposure, a more practical aspect of attending an introductory engineering program may be to earn college credits from Johns Hopkins University (JHU). College credits have three utilities: (a) enhances the student's college application, (b) makes college education more affordable, and (c) reduces the course load in the initial year and allows the student to settle into college at a convenient pace.[5,6] At present there are a large number of introductory engineering programs, however, rarely are these programs ABET accredited and provide transferable college credits to high school students. On the other hand there are a vast number of courses at community colleges and universities, which allow high school students to earn college credits by attending specific courses; however, such courses are not specifically designed for high school students. Moreover, such courses often do not give fundamental understanding about engineering disciplines to high school students via rigorous experimental approaches or hands on experience.

Introductory engineering programs for the high school students vary dramatically in their content and nature of instruction. Some of the popular engineering introduction programs are iD Tech camps, NASA SHARP program, National Youth Science Camp, Student Materials Camp, introduction to engineering program at University of Notre Dame etc. Most of the existing programs, which serve as the bridge between high school and college programs in engineering, have the following shortcomings.

(1) Highly specific to an engineering topic, or too generic to give a critical level of understanding about engineering basics.
(2) Less emphasis on engineering fundamentals, more emphasis on demonstrations
(3) Instructors are generally skilled in one engineering branch and do not have sufficiently clear understanding about other engineering disciplines, to incite genuine interest in other areas. For instance an instructor with electrical engineering background is highly unlikely to teach the concepts of civil engineering.

To overcome the above stated shortcomings, the Center for Educational Outreach at the Whiting School of Engineering at the Johns Hopkins University offers Engineering Innovation (EI) for high school students.[7] EI is a four week long summer program that exposes high school students to major engineering disciplines like mechanical, civil, chemical, electrical, and materials. EI is a condensed version of *EN.500.110 What is Engineering?* This course was designed by Dr. Micheal Karweit for the students with undecided engineering major at JHU. This paper discusses the EI program and its salient features in preparing high school students for the engineering profession.

2. Introduction of EI program: EI program benefits high school students in three main areas: (a) introducing them to various engineering areas, while improving their STEM skills and self-efficacy,[8] (b) provide college credits[5] to eligible students, and (c) mitigating the disconnect between college and high school education.[9] EI is becoming popular and increasing number of participants are joining this program, not only from the USA but also from the abroad. In 2011, 307 high school students attended EI program at various sites in the USA (Fig. 1). During 2011, following 16 sections were taught in three states (Maryland, Pennsylvania, and California) and the District of Columbia:

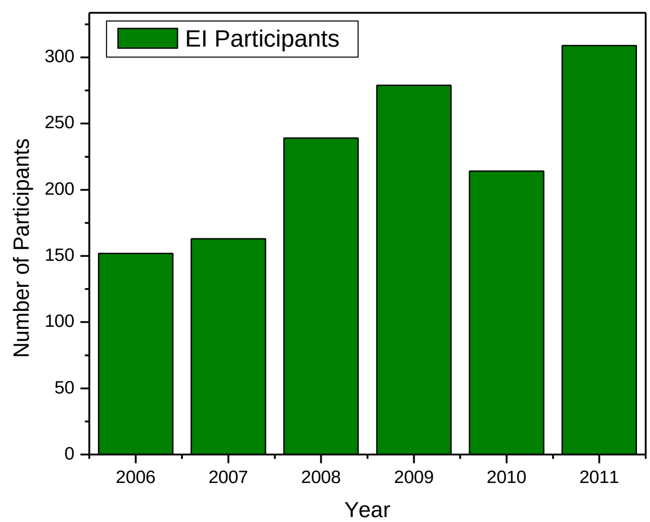

Fig. 1: Number of participants in EI program conducted from 2006-2011.

- California Lutheran University located in Thousand Oaks, California
- California State University, Fullerton (CSU Fullerton) located in Fullerton, California
- Eastern Technical High School located in Baltimore, Maryland
- Johns Hopkins University, Elkridge campus (JHU Elkridge) located in Elkridge, Maryland
- Johns Hopkins University, Homewood Campus (JHU Homewood) located in Baltimore, Maryland (four sections – A, B, C, and D)
- Johns Hopkins University, Rockville campus (JHU Rockville) located in Rockville, Maryland (two sections – A and B)
- Tuscarora High School located in Frederick, Maryland (two sections – A and B).
- Pasadena City College located in Pasadena, California
- Sci-Tech High School (Sci-Tech) located in Harrisburg, Pennsylvania.
- University of Baltimore (UB), located in Baltimore, Maryland
- University of the District of Columbia (UDC) located in the District of Columbia.

For every site, an instructor, generally with a PhD degree in an engineering discipline, and a regional high school teacher, generally with several years of teaching experience, are paired to conduct the EI program. Before the beginning of the actual EI program, instructors and teaching fellows undergo one week of rigorous training at Johns Hopkins University campus. During training instructors and teaching fellows are briefed in teaching fundamentals of multiple engineering disciplines. During training instructors and teaching fellows conduct a variety of engineering experiments which the high school students will be required to do under the EI program for their problem based learning.[10]

EI course include the lecture and experiments pertaining to a number of important engineering disciplines.[7] In order to connect the class room instructions and the experimental learning to the real life applications, students are asked to apply material they have learned to make functional engineering systems. The engineering systems that student produce are designed to emphasize the core concepts of specific engineering streams.

To teach the components of mechanical, materials and civil engineering EI students make bridges. The bridge is expected to be made up of various trusses. Students are taught civil and mechanical engineering fundamentals to design trusses. Trusses are made up of various types of spaghetti; a cheap material which shows students that this edible stuff can be a resource for learning engineering. Spaghetti are the structural material for the truss, hence they are extensively studied under the materials experimental lab. In the materials lab, students measure bending, tension, and buckling properties of the various widths of spaghetti. After understanding the various types of material properties, students design individual bridge segments and justify their dimensions. The materials lab is one of the major components of the EI program, and serves multiple purposes. For instance, students learn how to analyze a large set of data using Excel, do error analysis and, more importantly, develop a representative mathematical model from the experimental data. Developing the representative mathematical model from the raw experimental data teaches students how to approach a new and vaguely defined real-life problem. Such skills are the core strength of an engineer or scientist which is generally never taught by a formal course; a student learns them as the need arises and in varying degrees. It is a major drawback that such skills are not discussed in general context and that their connection to science and engineering problems pertaining to real-life situations remain incompletely explored. EI endows high school students with the ability to deal with new technological problems via simple yet well-designed hands-on experiments.

The EI program acknowledges the fact that most of the high school participants did not take preparatory courses to assimilate engineering concepts. To bridge the knowledge gap and to provide an inquiry-based teaching of engineering fundamentals, generally the EI instructor presents interactive lectures on the major topics. For instance, before the materials lab, a classroom discussion is presented about the materials properties, usage, and testing. In order to use a material as a structural material students are taught statics. Students are asked to apply their understanding about statics in virtual experiments. In a virtual bridge designer experiment, students design their bridge and analyze the nature of compressive or tensile loads on the individual components of a bridge. After selecting a bridge design, based on their understanding of statics, students construct individual trusses/ bridge components utilizing their knowledge about spaghetti's tensile, buckling and bending strength learned in the materials class and lab.

To further teach the civil engineering basics or at least a small component of it, students perform a remote measurement lab. This lab utilizes a meter stick and string as the surveying tools to measure the aerial distance between the apexes of two multistory buildings. This outdoor lab teaches the ways to estimate engineering quantities using limited resources. Students apply trigonometry to accomplish the assignment and determine the systematic and random type common errors in their measurements. This EI assignment also let students experience the utility of learning math and their applicability in engineering and science.

To teach the electrical engineering concepts students are engaged in developing a microcontroller based mechanical system, which is a light sensing robotic car. Students are taught about the procedure to develop microcontrollers performing the intended tasks. To guide the students through the complex concepts, students are taught about the logic circuit and how to develop it by using Boolean logic and logic gates (mainly NAND gates). This lab also enables the students to understand the basics of robotics and associated challenges. Developing a logic circuit from scratch and then seeing it functioning successfully is one of the most positive experiences that students had from the EI program.

To teach the chemical engineering basics, students first attend class discussion on important chemical engineering processes like chemical separations, chemical reactions, diffusion, chemical reactor design, and concepts of mass and energy conservation. Then students take part in a chemical processes lab to experience important chemical engineering steps. Chemical separation is the main theme of the chemical lab. Students do ethanol distillation from a mixture of water and ethanol. Students also do chromatography-based chemical separation. Students discover how to use a hydrometer and the Maccabe Thiele diagram for quantifying the distillation efficiency.

EI recognizes that successful and meaningful engineering careers involve understanding of various other subjects, not just mastering technical skills. Other subjects, which EI also includes in its curriculum, are professional ethics, finance, communication, and the ability to estimate.

To teach the vital role of ethics in engineering and science, an interactive session is designed. Different EI instructors conduct their ethical education session in various ways; generally by presenting numerous past ethical cases which adversely impacted economy, safety, or social wellbeing. Ethical education is imparted through discussion on the variety of case studies or hypothetical situations. Students explain their stand with regards to individual case studies. Through discussion with peers and instructors, they realize that in many cases the difference between right and wrong is not obvious. Interestingly, in the beginning EI students appeared to consider ethical discussion unnecessary or not important as they seemed to be content with their own ways of justifying right and wrong.

This program also includes discussion and assignments on the role of money and finance in engineering. Students perform calculations to understand how the value of money changes with time. They are asked how a long term project may be impacted by the changing value of money and the availability of finances. The EI lesson focuses on inculcating the importance of time and money in engineering. EI students are exposed to several types of interest rates, inflation, and methods of justifying long term finance via various strategies.

Engineering is heavily based on communications. In engineering, it is crucial that one engineer effectively communicate the guidelines and instructions for the other engineers to enable the accurate, economical, safe and efficient completion of a project. For instance, design engineers must effectively communicate the design of an engineering system to the production engineers. To make high school students realize the importance of communication, a number of assignment and activities are incorporated into the EI program. EI students partake in an exercise in which they design a mousetrap within the suggested constraint. Then this documented design is forwarded to a second group of randomly chosen students to build the mousetrap just “based on written instructions”. Finally, the second group of students test their mousetrap design and give their feedback about the issues they encountered to the students who wrote the instructions. This is a simple yet highly efficient way to impart the importance of clear articulation and effective communication. In the second communication assignment, students are asked to propose a solution to a pressing technological issue and then market their ideas to other students via a group presentation.

Estimation plays a crucial role in engineering projects. EI students are taught that engineers and scientist generally do not have access to the accurate value of all the variables, and even that they may not be aware of all the variables. The ability to estimate engineering and scientific quantities with minimal error becomes crucial in making important decisions. To hone the skills of estimation, EI students are administered a variety of Fermi problems. In fact instructors use them as buffer activities to break the monotony of long lectures and other EI activities. Most of the time, the EI final exam for earning college credit also includes an estimation problem.

To encourage students to pursue an engineering career, the EI program conducts an engineering connection day. On this special day engineers from renowned companies like Northrop Grumman, Ford, local construction companies, active research scientists and higher education specialists are invited to share their insights and experience about engineering with EI students. Engineering professionals discuss their career journey, views about engineering work they are involved in, and their message for the budding engineers like the EI students. EI students have an opportunity to network and to get exposed to a number of engineering internship opportunities. For some sites, advanced degrees are also talked about. For instance this year the dean of the School of Engineering at UDC talked about potential advantages of higher education and numerous funding opportunities in graduate schools.

Along with the major EI activities, students are taught about graphing, report preparation, error analysis, dimensional reasoning etc.

In the final week of the EI, students work on a weeklong take home exam. Based on their performance in the final exam and grades in the EI assignments, which they did throughout the program JHU assigns their final grade. Also, in the final week of EI students work in teams to produce Spaghetti Bridge using their engineering skills. On the final day of EI, a bridge breaking competition is organized. Students test the strength of their bridges in the presence of peers, parents, EI staff and invited guests.

3. Program evaluation: The degree of success of EI program is measured by multi-faceted surveys. In the beginning of the EI program students are asked to fill out a pre-survey to record their skill levels, attitude for engineering, and future outlook. A similar survey is administered at the end of EI program to statistically quantify the impact of EI. In addition, EI alumni were surveyed to gauge the long term impact of EI on participating students. Survey of EI alumni was also important to map the EI effect from a new stand point. Alumni which are currently pursuing college degrees have a more matured and realistic outlook to reevaluate the EI effectiveness. For conducting these surveys and to evaluate the overall effectiveness of EI program an independent program evaluator was appointed. The external program evaluator also interviewed EI students and teaching staff about the various aspects of EI program. The findings and data discussed here is taken from the report prepared by the external program evaluator.[11]

4. Findings: EI program was attended by students of different demographics. Data suggest that female participation was 49% in the 2006 EI program. However, in other years it was significantly lower. In 2011 EI program only 26% of the participants were female (Table 1). Interestingly, the percentage of white students in the last three years have been in the 38-49 range; in the 2011 EI program it was 47% (Table 1). Percentage of Asian participants ranged from 13-29. Another interesting trend was observed with underrepresented minority participants. In 2006 it was 73%; however, this percentage dramatically dropped to 34%. Reduction in the female and underrepresented minority participants also appear to be correlated with the drop in the full or partial scholarships. Percentage of partially and fully supported EI participants decreased from 83% to 55%. It will be interesting and important to study if underrepresented minority and female participation can be boosted by the financial support.

Table 1: EI Student demographic characteristics.

Characteristics	2011	2010	2009	2008	2007	2006
% Female	26	31	31	37	32	49
% White	47	49	38	28	27	10
% Asian	21	29	25	22	13	14
% Underrepresented Minority	34	30	38	50	60	73
% Full or partial scholarship	55	47	54	66	72	83

EI program contents are considerably challenging. High school students are generally selected by ensuring that they have earned reasonable proficiency in math, science, and English. Majority of the EI participants took biology, chemistry, algebra, algebra II and geometry (Table

3). The percentage of students who attended trigonometry, pre-calculus, and calculus were 69, 68, and 26, respectively. As discussed elsewhere in this paper, students who attended trigonometry and pre-calculus were found to assimilate EI material more effectively and were more likely to earn college credits. This trend is consistent with the observation about students in STEM disciplines at UDC. Students who completed pre-calculus were highly likely to complete the college degree in time.

Table 2: Percentage of 2011 EI participants taking prior science and math classes

Courses	Percentage
Biology	86
Chemistry	82
Physics	53
Algebra	87
Algebra II	90
Geometry	91
Trigonometry	69
Pre-calculus	68
Calculus	26

EI program allowed 9 to 12 grade high school students to attend the EI program. However, 10th and 11th grade high school students formed the major part of EI classes. In 2011 EI program 10th and 11th grade students were 34% and 51% respectively. In 2011, 9th and 12th grade students were 2% and 5%, respectively.

Effectiveness of EI was measured by surveying the EI participants' response to questions about specific engineering skills before and after the completion of program. Tabulated results showed that EI program significantly enhanced a number of engineering skills (Table 3). EI participants showed the highest gain in using Boolean logic (38% increase). EI participants learned basics of Boolean logic and then developed understanding about various types of logic Gates (AND, OR, NOT, NAND, XOR etc.). Students performed experiments on virtual circuit builder computer program to develop circuit diagrams to control the direction of motion of a robot car. Next highest increase was the communication of engineering design (37% increase). During one engineering communication exercise EI students wrote instruction for another student to construct a mouse trap. Under another communication exercise students worked in group to present solution for present day engineering issues- under this exercise they first communicated with the team members and subsequently as a team they communicated with the whole class. A significant improvement was noticed in participants understanding about dimensional analysis. After attending EI program students were able to understand the essence of dimensional quantities; their ability to give examples of dimensionless variables improved by 36%. A major gain was noted in using Microsoft Excel® software for engineering calculation and analysis (36% increase). During in person interviews a number of EI participants expressed their amazement about the capabilities of Microsoft Excel® software. During the analysis of materials lab data students utilized Microsoft Excel® software to develop model for representing bending and bucking load as a function of length and diameter of the mechanical testing samples. Students also used this software to do error analysis and engineering calculations. Table 3 enlists the percentage improvement in various engineering related skills due to the EI program.

Table 3: Percentage of students who could perform skills before and after 2011 EI program.

Skill	% pre	% post	Change from

			pre to past
Use of Boolean logic	20	58	38
Write assembly instructions that someone else can follow	39	76	37
Give examples of non-dimensional variables	27	63	36
Use Microsoft Excel® to solve problems	43	76	33
Design and build a structure without a detailed plan	52	76	24
Describe uncertainty in a set of data using standard deviation	36	57	21
Apply data in scientific or engineering reasoning	55	77	22
Evaluate problems you've never seen before and whose answers can't be found in Google	47	67	20
Work with limits that are "proportional" to one another and not equal to one another	45	62	17
Use logarithms to analyze data	45	61	16
Describe equations using dimensions and units	61	76	15
Calculate a mean, standard deviation, and variance from a set of data	62	76	14
Deal with measurements that contain errors	54	68	14
Describe the properties of a force	50	64	14
Use a table of values to estimate a solution from raw data	60	74	14
Work with vector quantities	48	62	14
Develop your own problems or experiments to explore a concept or principle	50	62	12
Simplify a complex problem into a few key issues	58	70	12
Write a complex lab report that includes graphs and diagrams	59	71	12
Describe the physical properties of materials	69	79	10
Know when a problem isn't posed in a way that you can answer it	59	68	9
Estimate answers rather than calculating them	70	78	8
Make oral presentations to an audience	64	72	8
Sketch or draw two-dimensional or three dimensional objects	67	75	8

Use math to analyze data	74	80	6
Work with laboratory instruments or tools	78	84	6
Apply trigonometry to word problems	71	74	3
Identify when you don't know something in a problem	77	80	3
Visualize three-dimensional objects	73	76	3
Understand and solve word problems	77	78	1
Be a contributing team member	85	83	-2

EI program also provides college credits to eligible participants. EI program is ABET accredited and credits earned from this course can be utilized throughout the USA universities and colleges. To earn the college credit students are required to earn and A or a B in the course based on the final exam and in course assignments. In 2011 EI, 62% students earned the college credit. Percentage of student earning the college credit in the 2010, 2009, 2008 were 59%, 65% and 58%, respectively. Students' performance in EI program strongly correlated with their prior math preparation, which is in agreement with prior studies.[12-14] Data suggested that students with trigonometry and pre-calculus earned better exam grades and were more successful in earning college credits.

Finally students were asked to rate the EI program. More than 90% student rated EI program good, very good and excellent. More than 40% students rated EI program to be very good. This data signifies that EI program was a positive experience for most of the participants. According to interviews of numerous participants, EI program enabled them to appreciate the engineering from different angles, which they never imagined. It was also noticed that student tend to utilize their positive experiences in their high school classes. For instance, one 2010 EI participant wrote an essay during her high school class pertaining to the meaning of numbers, her new perception developed after attending the EI program. Beside this EI has produced long-term impacts on its alumni.

To study the long-term effect of EI program alumni were asked to participate in a survey. It was found that out of 102 surveyed alumni 80 alumni have made the decision about their college major. Cumulatively, 87% EI alumni are majoring in a STEM area (Table 10). Alumni who are majoring in engineering is 56%. This high percentage of EI alumni enrolment in STEM areas suggest that EI can play an important role in developing sustainable interest in STEM fields. This aspect is crucial because a large population of students who joined STEM area generally changed their disciplines after first year.

5. Summary: The core value of the EI program is that it teaches approaches to solving engineering problems and developing engineering aptitude. Students are given a number of individual and group assignments. They work in teams on major engineering experiments like: materials properties, structural design, robot construction, and bridge building. Prior to experiments, students take part in lecture and discussions on the relevant topics. The instructor and teaching fellow provide optimal pedagogy to foster independent critical thinking. During the EI program students are engaged in the discussion of professional ethics, engineering economics, and data analysis. At the end of the third week students are given a take home exam. Earning an A or B in this ABET accredited EI program make them eligible to get three JHU college level credits.

Acknowledgment: PT thanks Michael Karweit for designing engineering innovation program and nurturing it. PT also thanks Kathleen Dowell of EvalSolutions for the data analysis.

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