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University-community partnerships and program development in pre-college engineering education

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University-community partnerships and program development in pre-college engineering education

Abstract

With the increasing discussion on STEM principles in K-12 education, specifically on engineering skills and practicum, public schools look to university-based education researchers for curriculum development. These partnerships are low cost to the school district, yet they remain mutually beneficial. Such is the nature of the growing relationship between Tufts University and Somerville High School, which is initiating a four year “pre-engineering” program for students in its Center for Career and Technical Education (CTE) with the help of the Center for Engineering Education and Outreach (CEEO). This “pre-engineering” program draws from a number of introductory collegiate engineering and service learning courses, focusing on project-based, interactive class work, some elements of an inverted classroom model, and constructionism. Additionally, the program’s development reveals issues that can arise in community-university partnerships, specifically the vital importance of communication between both parties. Programs like “pre-engineering” also provide university students and faculty with opportunities for outreach and community involvement, incorporating a rare service record into the heavily prescribed collegiate engineering track. In this paper, we discuss these issues as well as the focus on engineering as more than a career path for students who are in accelerated math and science programs, stressing the importance of the social functions and components of engineering projects. We will also describe the four-year track that constitutes the “pre-engineering” program as an intentional progression from basic knowledge of structure, materials, and drafting to complete ownership over all components of an engineering service project in a capstone requirement. Each year builds an increasing awareness of the dynamic engineering design process as a guide, tool, and resource for engineers of all experience levels and fields. We draw upon appropriate math and science skills while also challenging students to consider budgetary restrictions, organizational efficacy, and knowledge of human factors. We hope to illuminate the mutually beneficial outcomes of these community partnerships and establish a solid framework for engineering preparation and instruction in secondary education.

Introduction

Recently, a partnership between Somerville High School and the Tufts University Center for Engineering Education and Outreach (CEEO) has emerged within the field of engineering education. In an effort to provide students in the center for Career and Technical Education with more post-graduate options, a “pre-engineering” program was devised to give students strong engineering content knowledge and the choice of several tracks. Ideally, we would like to give students the option to enter an institution of higher engineering education, a dedicated vocational program, or the workforce. To accomplish this, we have integrated research from many college level engineering programs as well as previous programs created by the CEEO. Further, we have noticed that the relationship between university and community can be misconstrued as a one-sided, university-to-community dynamic. We feel that this is a harmful assumption to make; communities have much to offer universities, and insisting that communities be the recipients of programs without offering their own contributions undermines the impact a community can have. Here, we describe the curriculum currently in place at Somerville High School in terms of its theoretical framework, the progression of content knowledge, and the reciprocal impact between university and community that programs like these can nurture. We feel that engineering education and outreach can be a powerful tool for building relationships between universities and communities through encouraging growth of content knowledge and service and dedicated involvement on both sides.

Theoretical Framework: Engineering Design

Improving engineering education has become a priority for education researchers across the United States. The movement has several different faces: some choose to create engineering programs as a part of their core curriculum (Massachusetts DOE, 2001); others choose to integrate engineering design concepts into other realms of science, math, and technology education (Katehi, Pearson, & Feder, 2009). The theoretical constructs behind both of these responses largely center on the inclusion of the engineering design process in student work and the importance of project-based class time.

The engineering design process (EDP) consists of distinct steps, visible to students, that engineers undergo to solve engineering problems independent of the discipline, be it civil, mechanical, chemical, or otherwise. The process also includes any kind of problem solving mechanisms, from specific content knowledge to peer review. This cyclical model is the core of engineering design curricula; once students understand its steps, they can continue to more independent projects that integrate more complex content knowledge. Therefore, it is the first step in a strong engineering education program (Hynes et al., 2012). Previous programs that use the engineering design process as a strong basis for engineering learning include the University of Colorado at Boulder's First Year Engineering Project, Purdue's Engineering Projects in Community Service (EPICS), Armstrong Atlantic State University's Talented Researcher in Engineering (TRIE) (Goeser et al., 2009), NASA youth programs, and the US For Inspiration and Recognition of Science and Technology (FIRST), to name a few. While these programs are not specifically created for high school curriculum, they provide positive evidence of students learning through design. These university programs also largely rely on engineering and service learning, a means of involving engineers in community service by engaging them in real world engineering problems that serve a nearby community.

Project-based courses are designed to helps students view engineering problems systematically and maturely (Crismond, unpublished). Each step of the EDP can be workshopped and assessed in a distinct module, and certain projects can stress some steps over others. See Figure 1 for an illustration of the EDP and each of its component steps.

Within this process, Hynes et al. (unpublished) describe how each of the steps affects students' understanding of engineering and their own projects. Similarly, Crismond (unpublished) shows how students tend to move predictably from immature to mature in their problem solving abilities. For example, when researching the problem (step 1), immature students tend to rush through key research steps, attempting to solve a problem that they do not fully understand. Mature engineers understand that a poorly researched problem cannot be solved efficiently. Therefore, a successful engineering curriculum must demonstrate the affects of both thorough and partial research, celebrating the former and explaining the negative outcomes of the latter.

Content knowledge, application, disciplinary integration, and teamwork combine within the EDP, making design-based projects an extremely meaningful learning experience.

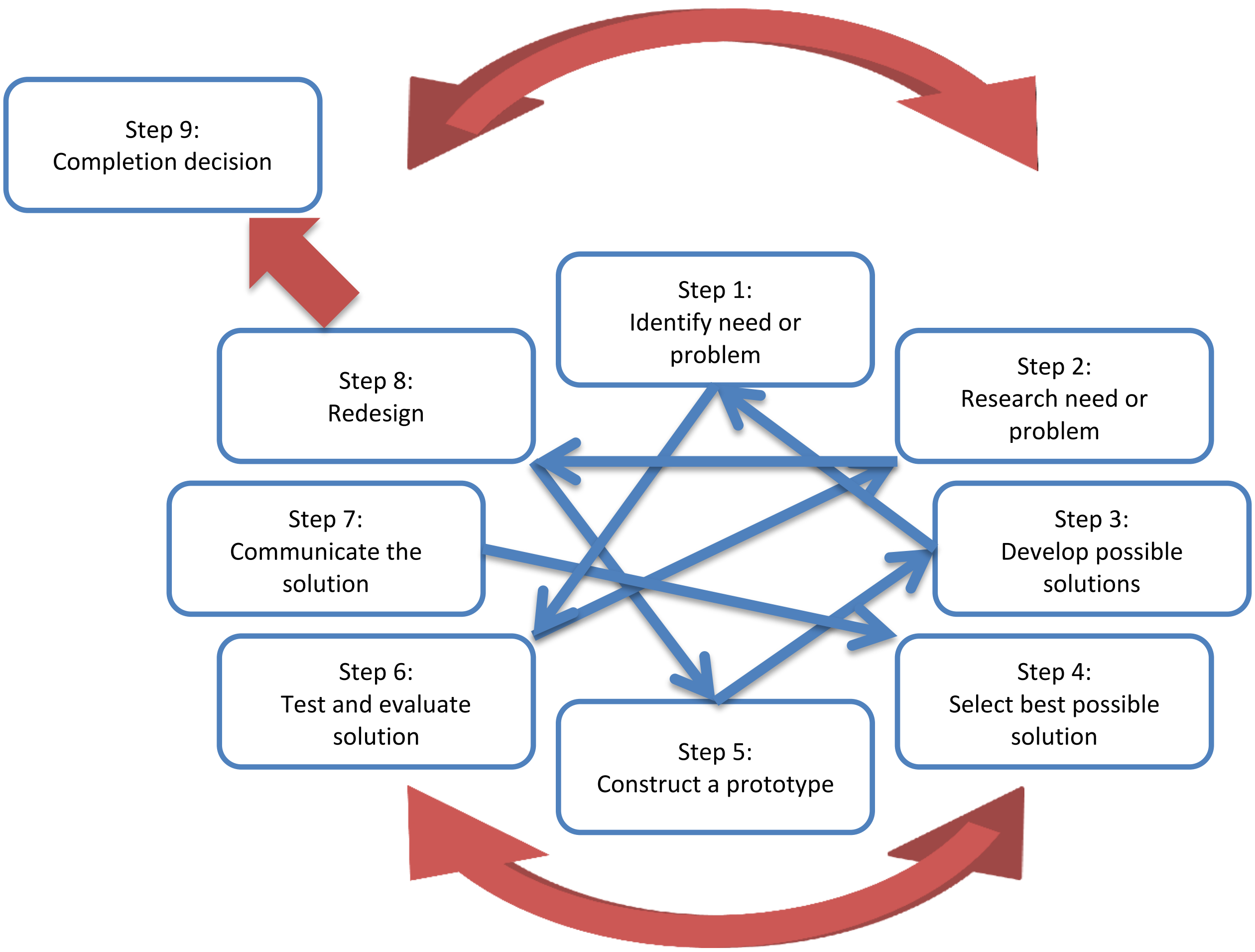

Figure 1: Engineering Design Process

Curriculum Description

To provide a frame of reference, we will briefly describe the first year of the four-year pre-engineering track currently in place at Somerville High School. First, it is important to provide an overview of our assumptions of students entering high school. In terms of their content knowledge, we assume very little other than their intuition of the way structures and materials work. We assume they have a curiosity about how the world works, an interest in science and math, and a desire to help others. We assume that the structures they have built have been limited to LEGOs or similar construction kits. Knowing that these students enter with considerable ignorance is vitally important and somewhat exciting. We are given the opportunity to frame engineering as a great deal more than simply “building things.” We can teach engineering as a process applicable to many disciplines, for the intentional, systematic progression engineers follow can be generalized to constructing a writing assignment, formulating or rebutting a debate argument, and creating skillfully crafted art or music projects. Therefore, Pre-Engineering 001 initially focuses on the Engineering Design Process (EDP) and its individual stages.

In accordance with Crismond's paper on scholarship of integration and informed design, we assume students to have an immature method of solving problems upon entrance into high school. The EDP, with its dynamic stages and the relationships and progressions between them, constitutes a mature system for solving problems and addressing challenges. Of course, all students address challenges differently, and the EDP is not meant to unify individual ideas into groupthink. The EDP provides a framework in which ideas can be solved creatively and reliably. Therefore, the learning objectives of Pre-Engineering 001 strongly emphasize the EDP with activities that focus on individual stages. Additionally, reflection sessions encourage students to engage in metacognition about their interactions with the individual stages, determining which stages they spent the most time on, which stages they had the most difficulty with, the stages they felt they neglected, and so on.

The curriculum begins with a paper engineering segment that progresses from problems that can be solved immaturely to problems that need a mature problem solving approach. The first project, an individual shelter built to scale, contains relatively few criteria. Mainly, it must stay together; it must fit a six foot tall person at 1"-1' scale (or similar); it must be made entirely out of paper with no tape or other adhesive; and it must demonstrate knowledge of an assembly technique like slit attachment, twisting, or folding together. The main objective of this project is to expose students to the constraints that materials can offer; they will begin to think about materials based on what they can do, not what they cannot do. This is one step towards mature problem solving.

Students' progression towards mature engineering is guided by the engineering design process, which becomes the heavy focus starting with a short project on paper airplanes. Students will go through the process many times, making airplanes, testing them, noting their weak points, observing other classmates' projects, redesigning and reconstructing, and repeating as necessary. This continues in the next project, where students are charged with making a paper tower with different sets of constraints. Teachers at Somerville High School adapted this project so that students would first build towers using no tape, then using a limited number of paper sheets and one strip of tape, then to an unlimited pool of both resources provided that students could justify why they needed additional materials. This is an excellent example of teachers communicating with university partners based on their own expertise and knowledge of their students.

At the time of this paper, the above projects have already been implemented at Somerville High School with considerable success. We look forward to the rest of the first year program, which will branch out from the paper engineering program into new resources and the mastery of new materials. The following project is adapted from the Brooklyn Tech High School's Cardboard Chair. The end goal consists of the construction of a full-sized chair made entirely out of cardboard that can support a 150 lb. person without failure. During the four-week project, students will build paper models, scale models from card stock and cardboard, and then engage in the full size construction. The emphasized learning objectives include knowledge of compressive and tensile strength, implementation of algebraic and arithmetical principles like scale, area, volume, unit conversion, and mathematical modeling, the creation and effective use of orthographic projections, prototypes, and three-dimensional models, and further understanding and implementation of the EDP. Clearly, we place great emphasis on both the engineering and mathematical principles associated with the construction of useful objects. Also at work are key social interactions between members of small groups. The successful creation of a cardboard chair requires cooperation, communication, and the ability to share within and take criticism from a community of engineers and learners. This project is meant to be a far leap from the more simplistic paper engineering projects described above; we challenge students with this engaging, fun, and oftentimes frustrating project purposefully, so that they understand the daily pressure that engineers undergo.

The curriculum enters a new realm in the following weeks, focusing on communication systems, computer programming, and marketing. Instead of placing emphasis on Computer Aided Drafting programs, we designed this curriculum to give students a clear understanding of the engineering of computer programs rather than only using computers as a design tool. The learning objects of this section include the understanding of syntax and computer programming languages using beginner tools like Python, the integral parts of communications systems like senders, receivers, encoders, and decoders, the creation of functions and mathematical operations to serve programming needs, and the notion of human factors or usability. The curriculum is not meant to emphasize the memorization of syntax phrasing or programming tricks; we use visual aids to show what is really happening in the system. For example, an entire class period is devoted to demonstrating the creation of the Fibonacci sequence using shoeboxes (variables) and LEGO™ pieces (values). Instead of learning about communication systems and computers on a surface level, we expect students to have a strong grasp of how programs work and be able to demonstrate a depth of knowledge through the creation of their own simple programs.

The second semester's projects are meant to give students more ownership over projects while giving them the necessary scaffolding and support to ensure their success. A substantial unit on insulation and thermal properties of materials marries principles of heat transfer, architectural design, knowledge of materials, and the cruciality of testing, retesting, and collecting data. Students build their own test chambers in which they will determine the best insulating material among a list of many different options. They will make predictions and hypotheses, create a testing model, implement the model, record data, interpret their findings, and report their material choices. Students should understand the roles of a number of factors like efficacy, efficiency, cost, and availability. This project allows students to practice building while exposing them to architectural design considerations without requiring them to build an actual model house. It is grounded in chemical frameworks, fostering a strong relationship between engineering and science.

The semester continues with a larger, multidimensional project that places heavy emphasis on blueprinting and human factors of design. Students will design a one story, one bedroom apartment for someone with a physical disability. Students will have to research the services available for physical disabled people and determine which of those features are important for their own design. They will go through several iterations of blueprinting, following the recommended guidelines for architects and engineers. Their final models, constructed in teams, will be heavily focused on providing services to those who need them, integrating an element of service learning into the project that will be very meaningful for engineering as a social activity. By pairing research and service learning, students gain a new perspective on the EDP, discovering how it is meant to help both the engineer and the client.

The final project of the semester allows students to utilize the full range of their creativity and engineering knowledge; they are charged with creating an office workstation for the 21st century. With considerations toward new technologies and the ways in which people interact, students will create a scale model of a useful, marketable design. In addition to intensive design, blueprinting, and other engineering work, students are also encouraged to interview working professionals and draw from the work of other engineers. The project emphasizes the effective use of space in addition to many other engineering considerations they have already made in the previous project. Not only must they allocate space in terms of constraints, but they must also optimize the space for productivity and comfortable efficiency. This project is especially challenging because of how easy students interpret it to be. Students are quick to design a sensible space, and it becomes the teacher's role to challenge them to make their design stand out, reminding them that they will be pitching their design at a mock presentation. This project adds concepts of marketing and the business end of engineering. Students will also revisit basic ideas of civil engineering, but rather than focusing on tensile and compressive strength, they will instead focus on the client base that civil engineers serve. Students can also implement other varieties of engineering not yet explored like circuitry and electrical engineering. The outcomes of this project are multifaceted and will change depending on the group of students at work, demonstrating the creative license that engineering students should be encouraged to take.

The projects that form the foundation of this curriculum are meant to provide a diverse array of engineering knowledge and practice. We hope that students will find their engineering passion in one of these challenges. Students can then assume different roles based on their interests and strengths in the coming years as they engage in multidimensional engineering projects in their community. Further, this curriculum provides a week-by-week breakdown of the concepts and learning objectives, but it does not provide explicit lesson plans. Teachers are meant to bring their own expertise and nuanced instruction style to supplement this curriculum. In Somerville High School, teachers have already adapted this curriculum to better suit their areas of comfort; specifically, a teacher with experience in architecture has decided to shorten the computer programming lessons and place heavier focus on exploring materials, building techniques, blueprinting, and civil engineering principles. A teacher with experience in a technology field might do the opposite. As long as the learning objectives stay firmly directed toward the EDP and the associated engineering principles, students will benefit and perform well on standardized tests.

Reciprocal University-Community Impact

Engineering happens within communities of people. Overtly, fields like civil engineering directly affect communities with bridges, buildings, and other spaces in which people can interact. Less overtly, engineers provide services and products that community members may never see: improved software for companies, electrical infrastructure, optimized insulation materials and buildings, among many others. This is one of the initial learning objectives in an introduction to engineering for students of all ages. Therefore, it is key that engineering students, especially within university settings, have access to real engineering experiences in a community full of distinct, solvable needs. Unfortunately, universities are often perceived to have a negative impact on their surrounding communities. They frequently buy up nearby land that could go to other community members or services; they increase the cost of living; and they infuse the community with young people who come from very different places and may not understand the community's flavor or cultural makeup. This relationship is problematic from the beginning due to differing goals and populations on either side, but there are ways in which it might be improved. Communities have much to offer to universities, and a major contributor can come from the engineering department. Here, we describe the ways in which Tufts' involvement in Somerville High School has and can continue to improve the Somerville community and the growing relationship between university and community. Similarly, the valuable field experience and actualized engineering practice that university students can get as both engineers and mentors for high school students provides the university with learning benefits for its students, constituting a reciprocally beneficial support system for university and community members.

The Somerville community, located about three miles outside of downtown Boston, consists of a culturally diverse populace, and it is the second most densely populated city in New England. With origins as an immigrant haven due to laws of sanctuary, Somerville is home to many people of Brazilian, Haitian, and Dominican descent as well as Eastern Europeans. Somerville houses many commuters who work in Boston; it contains subway stations on two separate lines of the Massachusetts Bay Transportation Authority (MBTA) in addition to many bus routes. Although Tufts University is listed as a Medford, MA institution, half of the main campus is located in Somerville, and many students live off campus in Somerville housing. Somerville is a cultural and economic stew, and it provides fascinating opportunities for engineering students, opportunities that give both university and high school students an outlet for engineering practicum and service.

The Somerville community provides not only opportunities for university students to engage in engineering, it also provides students with the opportunity to create programs that address systemic issues of education. In the case of the new partnership between Tufts and Somerville High School, it provides both. Tufts students can become acquainted with the growing field of engineering education, designing curricula that address Somerville-specific engineering problems that high schoolers can solve. Tufts students and faculty must demonstrate significant content knowledge in engineering; in order to create programs that are intellectually appropriate for beginning, high school engineering students, the program designers must intimately understand the acquisition of engineering concepts. They must also understand pedagogical concepts, which constitute considerable challenges for many engineering students in universities. The community itself provides these opportunities.

For example, Somerville High School reached out to the Center for Engineering Education and Outreach at Tufts, indicating a desire for a new engineering program centered on an MBTA project. While the initial detail was vague, the principal of the Career and Technical Education (CTE) program made it clear that he would be able to get his engineering students involved in the extension of the MBTA Green Line into Somerville, a systemically important project for all community members. With this information, engineering students and faculty, in conjunction with education faculty, can construct a developmentally appropriate curriculum that isolates learning objectives for the high school students, develops projects, workshops lesson plans, and implements the program alongside Somerville teachers. Without the community programs like the Green Line Extension and the connections between community members like the principal and the project manager, Tufts could not begin to implement these new programs. As such, Tufts students gain extremely valuable insight into engineering concept implementation and educational theory. In addition, these university students can engage in service to the community in which their university resides, a key component of service learning.

Certain prerequisites for these kinds of relationships do exist. Mainly, it is vital that community members understand the helpful impact that a university can have and that they have a positive rapport with representatives in public works. In addition, it can be difficult for universities to reach out to community or small government organizations due to the stigma of university invasion of community lands and structures. In the case of Tufts and Somerville, we were fortunate in that Somerville High School's CTE principal initially reached out to the CEEO. Ideally, university citizenship programs should appoint staff members whose chief responsibility is to foster positive relationships with community organizations. These staff members can help identify community needs that the university can address using its resources in a mutually beneficial way.

This curriculum specifically demonstrates the reciprocal impact of university and community in several ways (see Figure 2). The Somerville community provides Tufts engineering educators with unique, multifaceted problems. For example, a recent project to improve a region of the city called Assembly Square consists of new shopping, entertainment, and residential structures that will impact Tufts student life. The project also consists of an additional MBTA station on the Orange Line, which many Tufts Medical students use frequently. Tufts involvement in this project would be extremely meaningful for the university, but the city would not easily allow engineering students from a nearby university to take any real ownership over the project. Project managers, though, have expressed real interest in involving the community's youth in the project as a means of public relations and deeper community involvement. We took these factors into consideration when building a curriculum for Somerville High School's engineering students. We isolated several different kinds of engineering at work: architectural design and civil engineering in the buildings, electrical engineering in the new MBTA station, and human factors. We also considered aspects of city planning like zoning, budgeting, and population displacement. Considering these as learning objectives, we designed the curriculum to engage students in these engineering ideas within a familiar context. Students practice blueprinting, orthographic projection, scale modeling, construction techniques, redesign, and many other aspects of the engineering design process. They interview project managers and other engineers. They are then given the opportunity to present an addition of their design to the project manager and the mayor, giving them access to a real world engineering experience.

Those positively affected by above example are clear. First, high school students benefit through the meaningful engineering experience and real world service they can provide to their community. Tufts University benefits by continuing to foster a meaningful relationship with its surrounding community as well as providing Tufts students with engineering education experience and a way to take direct ownership of a major community project. The Somerville community benefits by engaging its youth in a meaningful project as well as continuing a discourse on the development of its parks, businesses, and programs.

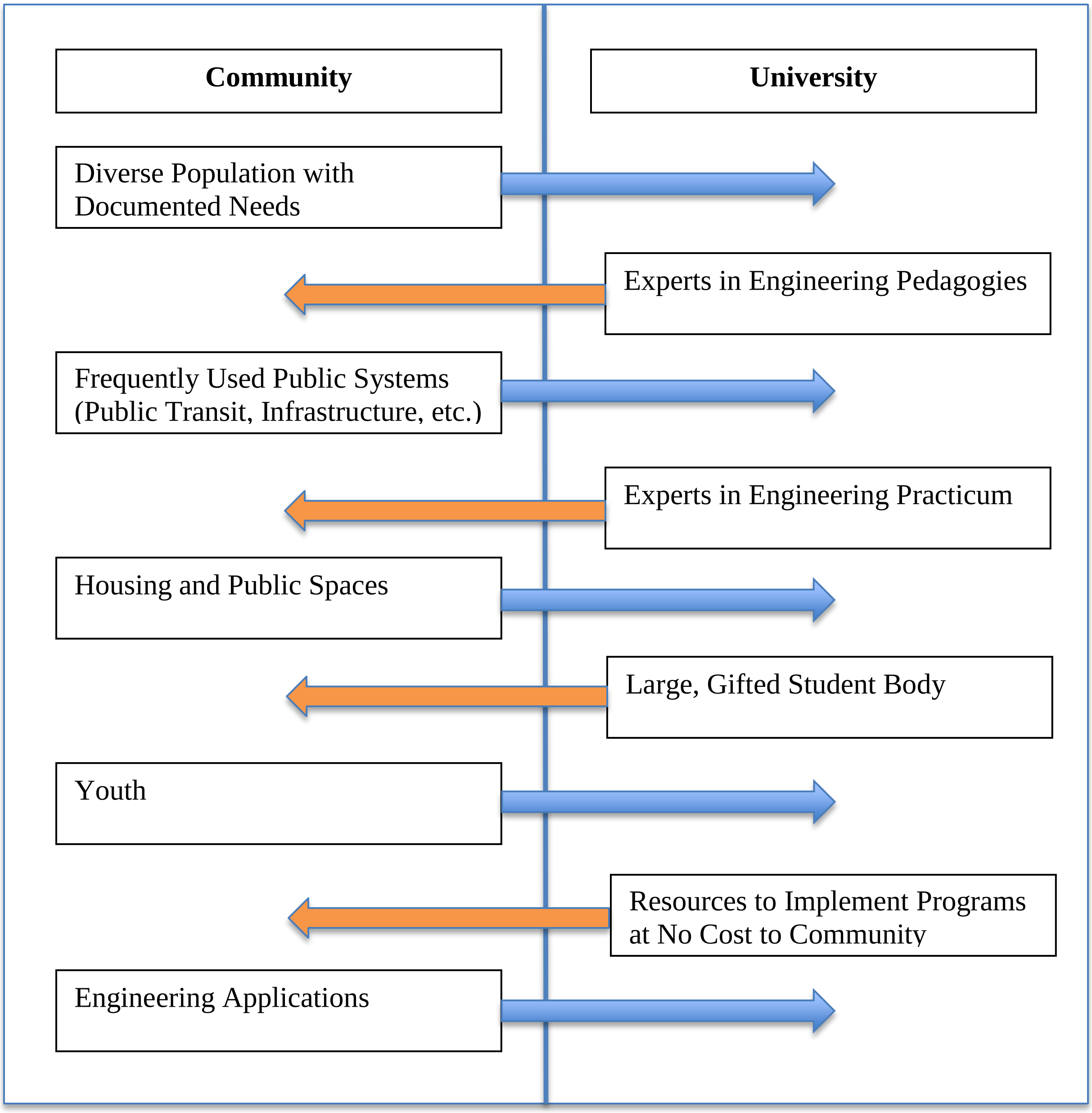

Figure 2: Reciprocal University-Community Partnership

Documentation

As the program finishes its first year, we will be collecting data on its impact and reception in Somerville High School. Informal interviews have shown that the activities and lessons are well-received by students and teachers. The freshman class currently engaging within the program has shown genuine interest in engineering as a social science, and their choice to continue with the program through the rest of their high school experience speaks to the engaging nature of the curriculum. In terms of hard documentation, we hope to standardize interview questions that we pose to teachers to assess their pedagogical knowledge, their feelings toward the curriculum content, their attitudes toward specific activities and concept instruction, and other concerns that they may have. For students, we hope to introduce an interview system that assesses their grasp of engineering content knowledge, their attitudes toward engineering in a community, their comfort level with higher level engineering concepts, and their enjoyment of learning about engineering.

The true litmus test for this program comes in the form of the Massachusetts Comprehensive Assessment System (MCAS). Every public high school student in Massachusetts must pass at least one science MCAS in order to graduate, and we hope that this engineering program will encourage students to take and pass the test of Engineering. We hope that students who might struggle with the Chemistry or Biology tests (the only two other options they have as Sophomores, as Physics is not offered until their Junior year). This especially applies to English Language Learners (ELLs), who frequently struggle with science tests because of the demanding vocabulary combined with higher level content knowledge. We believe that these students will perform better on the Engineering test because the playing field is more level to begin with. Very few high school students, both English-speaking and English-learning, have previous exposure to engineering vocabulary and content knowledge, so the opportunity for ELL students to pass more closely mimics that of English-speaking students. Also, since this curriculum depends on the act of creating as an important route to engineering knowledge, language skills should play less of a factor than in a more lecture-based class like Biology.

We look forward to reporting a more specific documentation system along with hard data and results as the program finishes its second year. We expect that, even though the curriculum was not developed alongside the Engineering MCAS test, a very high percentage of students will pass. We also expect that students will report community-oriented feelings toward engineering and that teachers continue to provide the researchers at Tufts University with meaningful feedback that leads to even more successful programs in the future.

Conclusion

Programs like pre-engineering in Somerville High School benefit students through far more than instruction. In many ways a constructionist program, this four-year track requires that students build their own knowledge, not only of engineering, but also of the community in which they live. In addition, Tufts University has gained access to further outreach in Somerville, improving a sometimes-contentious relationship that many universities encounter. By drawing from largely successful engineering programs already in place, we have been able to provide a high quality program that allows students to take ownership over their engineering education track; they can enter engineering programs in university, receive vocational training in a number of fields, or directly enter the workforce. Previously, students in Somerville High School's CTE program graduated on track to enter the workforce or vocational training. The addition of a college track is extremely valuable to students who did not have that option in the past. As communication continues between teachers at Somerville High School and the CEEO, this program will be reshaped based on community possibilities and the school's needs. The ongoing changes reflect the "community first" mindset that motivates both university and community to provide the very best for the young engineers of Somerville.

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