Design by Thread: The E4USA Engineering for Us All Curriculum

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***Abstract*—In the past decade, reports such as the National Academies' "Engineering in K-12 Education: Understanding the Status and Improving the Prospects" (2009) have discussed the importance of – and challenges of – effectively incorporating engineering concepts into the K-12 curriculum. Multiple reports have echoed and further elaborated on the need to effectively and authentically introduce engineering within K-12; not just to address a perpetual shortage of engineers, but to increase technological literacy within the U.S.**

The NSF-funded initiative Engineering for US All (E4USA): A National Pilot Program for High School Engineering Course and Database curriculum was intentionally designed 'for us all;' in other words, the design is meant to be inclusive and to engage in an examination and exploration of 'engineering'. The intent behind the 'for us all' curriculum is to emphasize the idea of thinking like an engineer, rather than simply to develop more engineers. Therefore, the focus is not on 'how to become an engineer' but 'what is an engineer' and 'who is an engineer'.

This paper will discuss the design of the first iteration of the curriculum. The initial design was based on the First Year Engineering Classification Scheme, used to classify all possible content found in first-year, multidisciplinary Introduction to Engineering courses in general-admit (non direct-admit) engineering programs. The curriculum provides progressively larger engineering design experiences relating to student fields of interest and real-world problems. Course objectives are broken into four major threads. Each of these threads is woven through seven modules. The threads are: Discovering Engineering, Engineering in Society, Engineering Professional Skills, and Engineering Design.

The paper will describe the design and details of the initial implementation of the E4USA curriculum, focusing on the features that make this course suitable 'for all.'

Keywords—K-12 engineering, technological literacy, engineering identity, engineering design

I. Introduction

Recent years have seen an increase in the number and variety of engineering programs at the K-12 level [1]. However, the integration of engineering into the K-12 plan of study is not straightforward: the most prominent effort toward integrating engineering is its appearance in the Next Generation Science Standards (NGSS) [2]. Despite calls for more engineering in schools and a strong demand for engineers nationwide, engineering continues with issues of public perception and insufficient or nonexistent teacher readiness. Engineering involves open-ended, ill-defined problems with multiple solutions [3-5]. In fact, introductory engineering courses and programs at the university level are not standardized and often inconsistent, [6,7]; this does not portend well to high school programs.

The National Science Foundation funded the Engineering for US All (E4USA) project in 2018. This program was originally established with five partner institutions including The University of Maryland, Virginia Tech, Arizona State University, Morgan State University and Vanderbilt to develop a course to award college credit and to 'demystify' engineering for high school students and teachers. The goals of the program include establishing both the curriculum and teacher professional development [8]. The program has a long-term goal of standardizing high school engineering curricula to introductory college courses, an effort supported by a large group of engineering deans.

The E4USA course is specifically designed, as the name implies, "for us all." This is unlike most, if not all, existing high school engineering curricula. The intent is not to produce more engineers or introduce a specific set of rudimentary engineering skills, but to introduce a creative engineering challenge to teams of students who may not be predisposed to pursue engineering. This is one of the areas where the E4USA curriculum differs from college or university level courses. The focus is on imparting engineering-centric skills (e.g. teamwork, interdisciplinary thinking, critical thinking) rather than engineering content. The initial design was based on the First Year Engineering Classification Scheme, used to classify all possible content found in first-year, multidisciplinary Introduction to Engineering courses in general-admit (non direct-admit) engineering programs. From here, the introductory course curriculum was developed around the following threads: discover engineering, engineering design, engineering professional skills, and exploring the intersection of engineering solutions and society. Using a project-based curriculum, students will explore the definition of engineering as a problem-solving discipline, their engineering identity, how engineering is related to other opportunities, and the intersection of engineering, society, and ethics. The course offers students opportunities to 'think like an engineer' to develop and practice skills such as problem-solving, design thinking, creativity, innovation, and collaboration. Students have the opportunity to follow an engineering design process multiple times in the course to design solutions to problems. The curriculum has 4 'levels' of problem statement: basic problems defined by teacher activities in class, a local stakeholder who presents an opportunity to creatively solve a problem, engineering global challenges including the NAE's Grand Challenges of Engineering [9] and the UN's 17 sustainable development goals [10], and challenges arising in the student's personal life. Overall, the course design was developed using project-based learning approaches throughout the seven units that provide progressively larger engineering design experiences relating to student fields of interest and real-world problems.

II. Course Learning Outcomes

The course learning outcomes were developed through a series of workshops engaging experts in K-12 engineering. The initial E4USA workshop was held at The University of Maryland in December 2018 with over 100 attendees, from multiple universities, national research organizations, K-12 teachers, and other experts in attendance. Additional on-site working group meetings were held at The University of Maryland and Virginia Tech in spring semester 2019 and comprised of university faculty, high school teachers, and teacher professional development experts. The course learning objectives were initially developed based on the objectives and in consultation with the First-Year Engineering Classification Scheme [6] and framed by El Sawi's curricular development framework [11].

Understanding the objectives relies on understanding the goals of the course. The course is meant to introduce engineering to everyone, not just students with an engineering background or understanding, and certainly not only students who have prepared to enter engineering. For example, the math prerequisite for the E4USA course is algebra 1. The course is not intended to be a skills-based course: in fact, specific skills such as programming or CAD are not required (but may be used if applicable) [12]

The curricular structure was developed with the idea of spiraling complexity. Early units introduce tools, activities, and thinking styles in teacher-led activities with clear and concrete objectives, and then later units gradually give students more autonomy and more room to add their own creativity. Grouping the learning outcomes into 'threads' as described, enabled us to track these progressions and return to key objectives at multiple points throughout the course.

A. Discover Engineering (Red Thread)

The focus of the red thread is in the discovery of the holistic discipline of engineering and engineering identity (see Table 1). The discovery of what it means to engineer and to be an engineer is part of working towards an engineering identity. Critical reflection is a core skill developed throughout the course as a means to continue to build an individual understanding of engineering.

B. Engineering in Society (Yellow Thread)

The focus of the yellow thread is the intersection of society and engineering. Students explore the role engineering can play in the definition and solution of problems. Students must consider the applicability of engineering solutions and their effect on stakeholders through interviews and feedback with a 'client' in the local engineering challenge. Further, students will explore significant, globally impactful issues and issues on a local scale to better appreciate how engineering can be used.

C. Engineering Professional Skills (Blue Thread)

Objectives in the blue thread focus on professional skills widely found in first-year college programs and through the engineering profession. This section includes teaming, visual and verbal communication, and project management. As with all areas, these objectives will appear throughout the curriculum.

D. Engineering Design (Green Thread)

The green thread will lead students through a process of engineering design. Notably, there is not one specified design process, as many different processes are in use in K-12 and first-year curricula such as those specified by TeachEngineering [13], VEX Robotics [14], NASA [15], or others. Upon examination, the different processes are very similar and lead students through practically the same iterative steps [16].

Students will have multiple opportunities to proceed through the design process.

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Table 1: Course Learning Outcomes

Discover Engineering	Iterate and evolve the definition of what it means to engineer and be an engineer.
	Awareness of changing perspectives on one's current identities with respect to engineering through regular reflection.
	Recognize the value of engineering for all regardless of one's potential career.
	Explain and apply ethical considerations when exploring an engineering problem.
Engineering in Society	Explore the impacts of past engineering successes and failures on society as a whole.
	Use systems thinking to propose and analyze the relationship between inputs, intention, and impacts of technology in society.
	Recognize and investigate the world's greatest challenges and the role that engineering plays in solving these challenges (e.g., Engineering Grand Challenges, UN sustainability goals, etc.).
	Integrate diverse disciplinary thinking and expertise to inform design solutions that add value to society.
	Identify and analyze issues when bringing a solution to scale.
Engineering Professional Skills	Apply strategies to collaborate effectively as a team.
	Use various forms of communication (oral, written, visual).
	Recognize when to use various communication tools based on audience.
	Develop, implement, and adapt a project management plan.
	Contribute individually to overall team efforts.
Engineering Design	Uncover a problem that can be solved with a potentially new product or process.
	Identify appropriate stakeholders and evaluate stakeholder input.
	Plan and conduct research by gathering relevant and credible data, facts, and information.
	Model physical situations using mathematical equations.
	Evaluate solution alternatives and select a final design by considering assumptions, trade-offs, criteria, and constraints.
	Use and recognize when to use computational tools.
	Create a prototype.
	Create and implement a testing plan to evaluate the performance of design solutions.
	Apply iteration to improve engineering designs.

III. Course Modules

The E4USA curriculum is designed as four 9-week quarters with a target of approximately 200 minutes per week of instruction. The curriculum is designed to give instructors flexibility with structure. For example, lessons taking students through the engineering design process for the first time are broken into each step of the process to ensure students avoid the temptation to dive in and solve the problem without considering each step.

A. Quarter 1: Introducing Engineering

The focus of the first quarter is to introduce 'engineering' as a discipline, especially one that is beyond 'science and math'. Engineering is presented as a means to solve problems in the context of our everyday life. Students develop their engineering identity. Note that care was taken to ensure that everyone and everything was not necessarily classified as engineering; instead, that engineering *has an influence* in almost everything we see and work within our day to day lives. The first two units concentrate heavily on the red thread, "Discover Engineering," with hands-on activities to discover engineering in real life.

Unit 1 - Engineering is… Everywhere

Students will explore engineering through the evolution of engineering products. They will define engineering by relating it to their future plans and engaging in two one-day challenges.

The lessons in Unit 1 ask students to think of their dream job and lead them through relating that job to engineering. Students are then asked to identify someone who might be considered an engineer, and why they could or could not be considered an engineer. Students are then asked to think about this person when they were the student's age and investigate their lives. These activities are meant to help students see their own engineering identity, with care to not try to convince students that everyone is / is not an engineer.

Students engage in multiple short activities in groups. The distinction between 'group' and 'team' is an important one in Unit 1, as effective teamwork is not covered until later in the curriculum. Activities include the design and construction of a robot arm and an individual study of shoe soles. The final activity is a dissection of a piece of hardware (which may be found in a thrift store) to reflect on how different engineering disciplines played a role in its development and manufacturing.

Unit 2 - Engineering is…Creative

The students engage in a guided whole-class engineering challenge tethered to a global issue. They are provided a related problem and design to then construct, test, and evaluate product(s) to address a need. The challenge for the pilot year was water filtration based on a discussion of the NAE Grand Challenges [9].

After the formation of teams and lessons on effective teamwork, teams go through the steps in an engineering design process step by step. Teams identify constraints and criteria for success, and brainstorm and select design solution(s) to pursue. Teams build prototype(s) and develop a test plan to test each prototype. Finally, teams have to discuss how their design can be improved and how to communicate their design to stakeholders successfully. In Unit 2, all students in the class are working on the same design challenge, so teams may develop similar designs.

B. Quarter 2: Applying Engineering: Generating a solution to a local problem

The focus in the second quarter is a design to solve a problem for a local stakeholder. The stakeholder should be someone outside of the class; they may be in the school or school district, or a local utility or business. The teacher will identify the location for an on-site visit where students will meet with stakeholders. The key feature of this unit is a 'Designathon', where stakeholders will give feedback to student designs.

Unit 3 - Engineering is… Human-Centered

Teams of 3-4 students will select a local problem to research, sketch, and then prototype a solution. This process will be an in-depth investigation into "What is the real problem" as well as stakeholder analysis. The goal is to understand the real problem, creatively construct a low-cost functional prototype and compare it to existing solutions that do not necessarily refine, iterate, or 'deliver.'

Unit 3 begins with the identification of student teams and the identification of an external stakeholder. Teams will brainstorm to discuss potential problems which can be solved with an engineering solution. Teams will engage the stakeholders with a field trip. Teams then go through a formal process of concept generation and selection, and work with communications via graphics, whether that be through sketching or CAD. The unit culminates in a Designathon, where invited students, parents, community members, etc. review designs pitched by student teams and provide feedback. This feedback is the foundation for Unit 4.

Unit 4 - Engineering is... Responsive

Creations will be presented at an in-school Designathon and to community partners for critical feedback and user input as the curriculum moves from Unit 3 to Unit 4. Design details will be documented in a case study.

Unit 4 begins with a Designathon debrief and a discussion on how to incorporate feedback. Teams continue to work on developing their solutions for the identified problems. As solutions are developed, solutions are prepared for peers and stakeholders. A formal presentation to stakeholders and reflection round out these units.

Units 3 and 4 in tandem represent the first time through an engineering design process for many students. Units 5 & 6 and Unit 7 will allow the same process for a more open-ended problem.

C. Quarter 3: Applying Engineering: Generating a solution to a global issue

The focus in the third quarter is a design to solve a problem for a more global problem or a local problem related to an identified global problem. For the pilot year, "access to clean water" was the selected theme of the problem to be solved.

Unit 5 - Engineering is… Intentional

Teams of 3-4 students will identify a global issue and will identify a local problem that is associated with the global issue identified. The issues and problems selected will be co-constructed by students and teachers. Student teams will create a video submission of a design brief in which they will justify their conceptual design concept and project management plan.

Unit 5 takes students through a design process but examines each step at a deeper level. Questions to be explored include: what inventions have changed the world? Further, why be concerned with ethics in design? Students explore high-quality targets for their solutions and explore the value in consulting with deep and diverse experts who may help design an optimal solution.

Unit 6 - Engineering is... Iterative

Team of 3-6 students will engage in all aspects of the design process during this unit. Students will build, test, and optimize a prototype of the solution designed. As time permits, students will re-design a solution based on what they learned from the testing of their first prototype to refine what they learned through iteration. Student teams will generate a comprehensive engineering design report and will provide a design presentation this quarter.

This unit focuses on the development of the prototype and the design of effective testing. The prototype proposed in Unit 5 is designed, critically examined, built, and tested.

D. *Quarter 4: Generating an engineering solution to a problem relevant to* you

The focus in the fourth quarter is an engineering design to solve a problem identified by the student and or student team. This student selection means that the classroom teacher can expect multiple and varied solutions to multiple and varied problems. The classroom is a project-based environment with progress and check-ins via a portfolio submission system.

Unit 7 - Engineering is… Personal

Students examine their day-to-day lives to find problems that can be tackled by teams of 3-4 students. The process leading to a design solution is student-driven, teacher-guided, and highly informed by the experiences from the previous quarters. This approach is an open-ended co-creation.

Unit 7 is truly open-ended. Students select their problem to solve and go through each step of a design process to develop a solution to that problem. One issue with module 7 is that teachers assume a different role than they typically would assume. Teachers inherently do not know the answers to the problems. At the university level, we would use a problem-based learning approach when appropriate, but it is not as common in high school. The teacher serves as a coach, facilitator, networker, or someone to encourage and help guide the team as they discover how to solve problems as they appear. Final solutions are documented and presented.

IV. Seeking Teacher Feedback

The E4USA project had a cohort of nine teachers in its pilot year. All teachers went through synchronous and asynchronous training online and a one-week in-person session at The University of Maryland in the summer. The professional development featured both engineering and curricular content. It also covered content that could prove problematic to introducing engineering to students with little to no understanding of engineering – from teachers with the same experience, such as implicit bias that could affect how individual students experienced the course.

Teacher input was sought throughout the course via a Canvas Learning Management Site (LMS) at The University of Maryland. Teachers were asked to reflect regularly. The entire cohort was brought to a mid-year workshop at Arizona State University for professional development on Units 5-7 and to seek feedback through a different mechanism. Finally, teachers were asked to comment directly on google docs of the units and lessons.

A. *Teacher feedback*

Two main issues were prevalent throughout the feedback. First, there was a concern that additional time spent in the beginning modules meant that Units 5-7, the more open-ended portion of the course, would be restricted or reduced. The curriculum design team plans to revise the next iteration of the course to allow teachers to pursue Units 5-7, or alternatively, Units 5-6 only or Unit 7 only, depending on their comfort level with truly open-ended problems.

Second, some lessons were combined or skipped. In many cases, this was not important based on the intended flow of the curriculum. However, some modifications were not as effective. For example, at least one teacher introduced effective teamwork skills prior to Unit 3, where they are internationally first introduced. The intent was for student groups to proceed through some activities as a group as opposed to consciously striving toward common goals or working as a cohesive team. In some cases, the combining proved to be positive, and the curriculum development team has combined some of these lessons.

It is important to note that most teachers had progressed into Unit 5 and had student teams ready to proceed through a design process when the March 2020 COVID-19 pandemic forced schools to close or go entirely online. As with nearly everything else across the globe, this pandemic disrupted the course and the feedback we expected to receive. The following year will serve as a pilot for the later units.

V. Curricular Modifications

The curriculum instituted in the pilot year is to be refined based on input from stakeholders – primarily, teachers and students from the first year. The course objectives remain unmodified, as presented in Table 1. The seven-module structure also remains, although modifications are found in lessons with the units. In addition to slight editorial changes, the teachers and students identified areas where additional information would prove beneficial. Examples include effective teaming, where material and external resources are added, and project planning, where different methodologies are introduced and external resources identified.

One modification to the structure is to remove activities from lessons and create files on their own and to ensure that each activity has an associated assessment. This restructuring will help the E4USA team with TeachEngineering, a popular site for teachers with lessons and activities. This site will give the E4USA curriculum a home that should be readily accessible as the E4USA team expands from its initial cohort of nine teachers to a planned cohort of approximately 40 teachers in its second year.

Finally, some individual lessons are being combined while keeping the emphasis on following an engineering design process in a step-by-step fashion.

The COVID-19 pandemic has provided a somewhat urgent discussion on transitioning the curriculum to an online or hybrid curriculum. While most of the initial cohort will finish the course as an online course, as is the case with most engineering courses, this was neither planned nor intended. Conversation on how to transition the curriculum to an online course has commenced, but this is a long term plan as opposed to the short term. At the time of writing this paper, the intent and hope are that schools offer the curriculum next year as it is designed – in the classroom.

VI. Conclusion

The E4USA curriculum has been developed and piloted with the intent to introduce engineering "for us all" in an effort to expand technological literacy and allow a diverse group of students to explore the nature of engineering. Initial feedback showed that the curriculum was quite successful in helping both students and teachers build their engineering self-efficacy and establish their engineering identity. Significant feedback was given by the initial cohort of teachers and incorporated into a second version of the curriculum. Based on initial feedback, the course is meeting its intent to:

- Establish a means for students to explore engineering in the context of its interaction with society and as a means to solve problems
- Establish a path toward college credit for students who complete the course, and
- Promote technological literacy

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