The Prototyping of Human-centered Design Engineering Curricula to Address Global Environmental Challenges

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Introduction to Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) Curricula

Engineering embedded in a liberal-arts education provides unique opportunities [1] to integrate interventions within the curriculum. Cognitive approaches such as design and innovative thinking can be integrated into the curriculum and can be implemented through active learning and human centered design methodologies. We incorporated these methodologies into our curricula to prepare students to address the ever changing and complex environmental challenges that affect society [2]. Traditional lecture-based learning does not provide adequate preparations for students to utilize their learning and apply their knowledge in various real-life scenarios outside of the classroom. Problem based learning provides a novel teaching and learning model where students interact with concepts and respond to challenges in workshops settings and apply their knowledge, fabricate and build prototypes to test different hypotheses. The classroom becomes collaborative environment among students and, faculty, and staff, working together to respond to the challenge. Instructors provide different scaffolding to match the varying needs of the students through the design process as well as support team-based project work [3-5]. This paper presents our methods for prototyping human centered design engineering curricula through summer programs.

While we initially created pilots with small groups of our college students to test and verify the effectiveness of complementary additions to the curriculum, the demand for more topics to test increased and made it difficult to adequately evaluate these programs. In order to evaluate and assess new experiments and projects, prior to introducing them in our curriculum, we use summer programs with different students to develop content and test learning objectives. We introduce the new topics to a cohort of students of diverse cultural background from local and international students. Our methodology is similar for the curricular development of each program (Figure 1) and consists of four main and distinct stages: (1) planning and administrative preparation, (2) content development and small-scale testing, (3) deployment and daily student assessment, (4) reflections, modifications and adjustments for a final course implementation. [6]

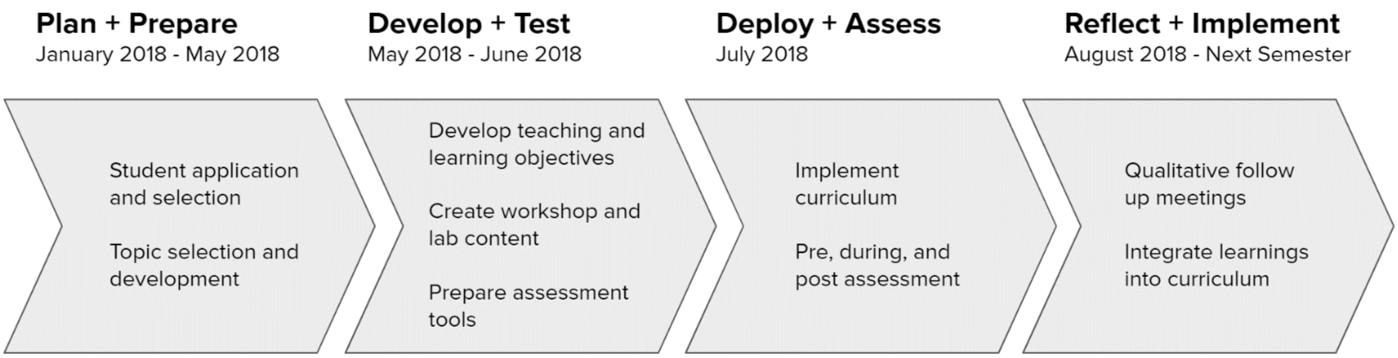

Figure 1: *Curriculum development process diagram*

The work described in this paper is focused on methodologies for addressing factors influencing the success of two programs as case studies, including:

1) Creating the cohort: evaluating and selecting students from different backgrounds and forming program leadership
2) Choosing the piloted topic to support introducing new content to our college curriculum
3) Developing the new content, including program workshops and collaborations among faculty, staff, and labs personnel
4) Mechanics for piloting the new activities and engaging with the participating students
5) Assessing the learning outcomes before, during, and after program completion

Description of the Two Programs

The first program is an introductory, pre-collegiate program focused on international water engineering and resource management with emphasis on ocean plastic pollution. The second one is a collaborative international exchange program for undergraduate students, centered on developing onsite soil testing devices for small scale Peruvian farmers (Figure 2). These two cases will be used as prototypes for developing curricula.

	Program One: Introductory Design Engineering	**Program Two: Advanced Design Engineering**
Topic:	International water engineering and resource management	On site soil analysis device for Peruvian farmers
Duration:	2 weeks	2 weeks
Cohort Composition:	12 international high school students (4 USA, 4 China, 3 Kenya, 1 Hong Kong) with no background in design thinking	8 international undergraduate engineering students, (1 USA, 7 Peru) with introductory backgrounds of design thinking all juniors in their third year (4 Mechanical Engineering, 2 Energy Engineering, 1 Environmental Engineer, 1 Industrial Engineer)

Learning Objectives:	- Apply foundation in design thinking to tackle open ended problems - Decide how to scope down problems and choose clients through research and empathy work - Learn how to work in collaborative environment	- Gain new understanding of designing in systems - Apply design thinking process for iteration on previously made prototype - Combine previous background and experience with new skills to work in collaborative teams to solve problems
Methodologies:	Systems Design Thinking, Human Centered Design, Rapid Prototyping	Systems Design Thinking, Human Centered Design, Rapid Prototyping
Proposed Client:	Multiple to be selected by teams through research	Previously conducted ethnographic research with community of Peruvian farmers
Design Cycles:	Multiple supported by exercises, workshops, and lab time	One iteration on prior prototype through guided week in the lab
Faculty and Teaching Staff:	-Assistant Dean for Teaching and Learning -Active Learning Lab Educator, Mech. Eng. -Active Learning Lab Educator, Bio. Eng. -Teaching Fellow, Bio. Eng. -Teaching Fellow, Design Eng.	-Assistant Dean for Teaching and Learning -Prof. Materials Engineering, SEAS -Active Learning Lab Educator, Systems Eng. -Active Learning Lab Educator, Electrical Eng. -Active Learning Lab Educator, Comp. Sci.

***Figure 2**: Details for each program*

The topics for each program were identified by faculty and chosen based on course development needs. These topics represent examples of 21st century open-ended environmental challenges that require novel interventions solve [7-8]. While the introductory program uses multiple iterations of design and testing, the advanced program has a schedule equally split between a focus on concept development workshops and followed by a single longer design cycle. The philosophy behind the structure for both programs is to develop a balance of theory and critical thinking skills and deep integration of hands-on design projects. During the course of study, the instructors emphasize the skills for solving problems through iterative feedback, and give students a thorough understanding of the design process as well as the tools needed to solve complex human challenges [9].

Special attention was made to create diverse cohort and admit students with diverse backgrounds (Figure 2). The main criteria for selection included previous academic experience and achievements as well as individual interest in the selected topics. Thus, students of similar backgrounds and from different countries joined these programs. Through these two programs, we tested parameters such as the influence of pre-program preparation and prior knowledge on the ability of the students to participate and learn during and after the workshops. These observations and evaluations were carefully made by our curriculum development and teaching staff.
We believe that the data collected from these programs provides better insights to developing introductory engineering courses for educating non-engineers, as well as engineering concentrators with limited knowledge in the subject matter. The pre-collegiate course tests content and pedagogy

for introductory level courses , and the collaborative exchange program is more suited to test the more advanced levels.

Assessment Tools Used to Evaluate the Programs

The learning environments that we created to address complex challenges give us the opportunity to assess student's development skills as well as their understanding of design as an intervention process. These capabilities were assessed at different stages, including before, during, and at the conclusion of the program. We performed these assessments through surveys and tested the self-rated confidence levels of the students as different material and content were presented. This enabled us to measure the effectiveness of the workshops and have feedback for future development [10].

Questions that assessed understanding-confidence of the students were framed for each specific session and students were asked to answer qualitatively, on a scale 1 to 5, the following questions: "How confident do you feel about using the content you learned in an applied setting such as a test or experiment?" During every day of the workshop, students applied their knowledge, and this was highlighted in the program's schedules; see Figure 3a and Figure 4a - in gray. Additionally, there were open ended questions for feedback on different instructors as well as a group reflection for how each team of students work together. At the end of every day, the data was anonymized and shown to the teaching staff. This provided prompt feedback and help created the needed changes.

The self-measured confidence provides us with a proxy to see how the students are responding to each session as well as measure their overall growth in mastering the skills needed to prototype and test what they have learned [11-12]. It also helped step beyond the boundary of knowledge tested for students to evaluate the context for where their knowledge and skills fit in as well as understand the context for what more there is to learn. We believe if the students were more comfortable with handling uncertainty as well as developed a critical mindset for how to approach the problem, then they would be able to more directly apply what they have learned in the classroom to real-world challenges. Confidence was self-rated (1 to 5) for each lecture and workshop and re-assessed after a lab setting. Effectiveness was also rated (1 to 5) with average scores compiled for analysis across the cohort. Relevance was calculated through students circling as many workshops as they deemed beneficial to that lab session. Total scores for relevance were then weighted for frequency by dividing the number of times that workshop for following lab sessions.

In our assessment, testing the level of confidence is adequate for the need of evaluating outcome because it helped us understand each student's degree of understanding and agency for application. Focusing on global environmental changes, the curriculum extends beyond the classroom exercises and aims to equip students to bring back what they learned and apply it in their own environment as they work with different clients to implement change. In both programs, finishing students who reported high confidence levels, and in follow up interviews, had examples of extended application beyond the scope of the classroom. For example, a group of three high school students from Kenya who finished the introduction program, developed a water filter system for their village in the following months. This is now a viable business providing support and infrastructure for their community. In the advanced program, the new soil testing prototype was brought back to the group of Peruvian farmers and is being continuously iterated on based on feedback gathered for efficacy in use.

Introduction to Design Engineering: Global Water Challenge

It is becoming clear that the understanding of evolving technology is essential for devising solutions to human challenges. Harvard SEAS curriculum design responds to this need by designing and delivering multidisciplinary, open-ended, multi-dimensional problem-solving courses. Our summer programs provide a suitable platform for developing such courses. The *Water Engineering and Resource Management* summer program focused on global water challenges and the design process in generating solutions. Our student selection criteria were guided by the universal nature of this challenge., hence we admitted students from China, Kenya, and from Flint Michigan. The program provided enrolled students an exposure to a range of water engineering and management technical skills, including chemical detection of minerals and impurities, the design of water purification systems, performance assessment, quantitative analysis and simulation (Figure 3a). Additionally, the program focused on users and economic factors that are integral to creating a holistic design solution. With such understanding of users' constraints and needs, problem definition, communication with a client, and documentation and communication skills, students ended the program with a comprehensive set of problem solving skills, and developed a research and design project that addressed water challenges in an underdeveloped community.

Students played a significant role in shaping this program, from articulating their interest in the program, setting clear project deadlines, determining leadership roles, to managing group dynamics, thus learning critical project management skills. They worked in groups of 3-4 students to research and select their own client to scope water contamination problems they would like to solve. Problems were defined initially as areas of opportunities [13]. Students were instructed to further define and articulate their clients' areas of concern and come up with a focused problem statement.

	Day 1	Day 2	Day 3	Day 4	Day 5
Session 1 10:00 – 11:30	1.1 Program Introduction	2.1 Design Thinking Intro	3.1 What Makes Water Drinkable?	4.1 Purification Methods	5.1 DIY Filter Building II
Session 2 13:00 – 14:00	1.2 Introduction to Active Learning and Lab Safety	2.2 Tools for Design: Rapid Prototyping	3.2 Intro to Methods of Water Purification + Testing	4.2 Redesign and Needs Assessment w/ LifeStraw	5.2 Finish Filter Testing
Session 3 14:30 – 16:00	1.3 Team Formation	2.3 Practice the Design Thinking Process: Partner Redesign	3.3 Introduction to Water Analysis + Testing	4.3 DIY Filter Building I	5.3 Presentations
	Day 6	**Day 7**	**Day 8**	**Day 9**	**Day 10**
Session 1 10:00 – 11:30	6.1 City Water Department Field Trip	7.1 Intro to Global Challenges	8.1 Gray Water, Desalination, and Intro to other Water Tech	9.1 Design Activity: Reducing Water Shortage (Prototyping + Group Review)	10.1 Documentation
Session 2 13:00 – 14:00	6.2 Water Treatment and Reuse at University	7.2 Microplastics Exercise I	8.2 Introduction to Systems Thinking and Research	9.2 Water Justice Lecture	10.2 Final presentations
Session 3 14:30 – 16:00	6.3 Tour of Stormwater Harvesting Systems	7.3 Microplastics Exercise II	8.3 Design Activity: Reducing Water Storage (Brainstorming Integrated Systems)	9.3 Design Activity: Reducing Water Shortage (Prototyping + Testing	10.3 Program Conclusion

Figure 3a*: Introduction program schedule and topics. Workshops are in white, and lab days are in gray.*

Overall Effectiveness		Overall Relevance	
6.1 City Water Department Field Trip	4.92	2.1 Design Thinking Intro	4.50
1.2 Introduction to Active Learning and Lab Safety	4.83	3.2 Introduction to Methods of Water Purification + Testing	4.19
3.3 Introduction to Water Analysis + Testing	4.73	2.2 Tools for Design: Rapid Prototyping	3.94
1.3 Team Formation	4.67	2.3 Practice the Design Thinking Process: Partner Re-Design	3.38
2.3 Practice the Design Thinking Process: Partner Re-Design	4.67	3.1 What Makes Water Drinkable?	3.25
3.2 Introduction to Methods of Water Purification + Testing	4.67	8.1 Gray Water, Desalination, and Intro to other Water Tech	3.25
6.3 Groundwater Tour	4.58	1.3 Team Formation	3.19
8.1 Gray Water, Desalination, and Intro to other Water Tech	4.58	8.2 Introduction to Systems Thinking and Research	3.00
2.2 Tools for Design: Rapid Prototyping	4.55	1.2 Introduction to Active Learning and Lab Safety	2.69
8.2 Introduction to Systems Thinking and Research	4.50	3.3 Introduction to Water Analysis + Testing	2.50
2.1 Design Thinking Intro	4.42	6.1 City Water Department Field Trip	1.75
3.1 What Makes Water Drinkable?	4.33	6.2 Water Treatment and Reuse at University	1.75
6.2 Water Treatment and Reuse at University	3.83	6.3 Groundwater Tour	1.00

Figure 3b*: Student effectiveness and relevance ratings for each workshop.*

As was indicated, the program included a rigorous daily evaluation of (a) the overall effectiveness of the in-class lectures and related training, as well as (b) the overall relevance of the covered topics, hands-on workshops, and team exercises - both toward empowering students to address the water engineering challenges at hand (Figure 3b). Most offered lectures appear to have been perceived as effective in students' minds, and that should not come as a surprise given the fact the lecturers were instructed to highlight the connections between the presented background material and the following hands-on exercises. Students have assessed ~20% of the workshops they attended as highly relevant to the open-ended water engineering design challenges. Interestingly, ~40% of the active exercises they were engaged with–mainly related to field trips to water treatment facilities and local purification systems—were assessed as less relevant to their design challenges. For this course, the introduction to the design tools and practicing their application with in-class exercises are three of the top most relevant workshops for students when they step into the fabrication lab setting and begin building.

The students' level of confidence was assessed as a function of workshops effectiveness as well material/topic relevance (Figure 3c). The data presents a positive view of the effectiveness of the taught lectures and workshops. More than 90% of the workshops were rated 80% or better in their effectiveness, which was matched to a great degree by students' level of confidence. As for material's relevance to program topics and related open-ended design challenges, 50% of the introduced skill-learning workshops were assessed by students to be 80% or better in their relevance to the addresses water engineering design projects. Almost 20% of these workshops were assessed "less relevant" by students, including field visits to water purification faculties and waste management operations.

Interestingly, students' level of confidence remained high even when they reported a low relevance of the presented topics to the execution of the design projects.

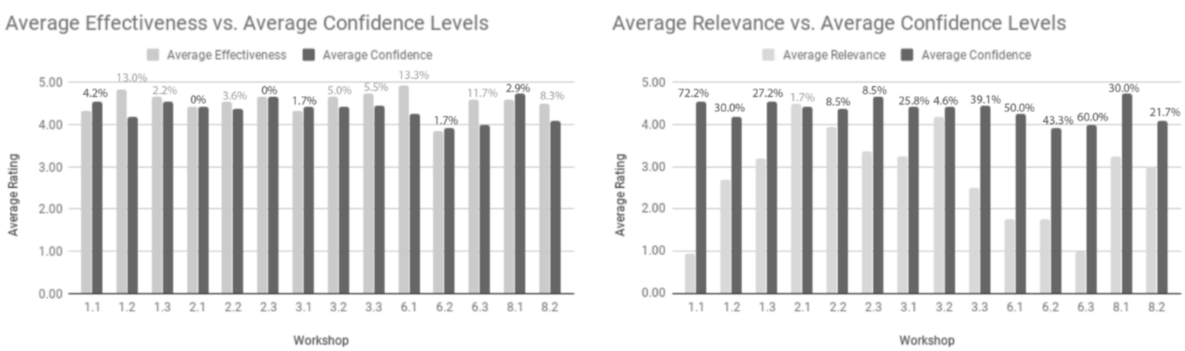

Figure 3c*: Assessment of students' level of confidence as a function of training effectiveness and topic relevance. The percentages highlight the delta between the two.*

Advanced Design Engineering: Agriculture Technology for Peruvian Farmers

The first two steps of the design process are empathizing with the end user and defining the problem. This connects the technical and iterative process of prototyping directly to the human centered side of the problem. For this summer program, third-year and fourth-year international engineering students from University of Engineering and Technology in Peru began with initial fieldwork, including interviews, surveys, and documentation, conducted with small to medium land holding farmers prior to their arrival. They also developed their first prototype based on initial findings in order to help farmers better understand what is happening between the soil and their crops at a specific time in the growing season. This helps dynamically respond to growing conditions and adjust what agricultural inputs are optimal. The co-production of knowledge and tools for stakeholders is especially important for the future work of farmers [14].

With varied background knowledge in environmental engineering and mechanical engineering, the students were most interested in learning aspects of the system they were least familiar with, such as the chemistry behind the soil analysis and how to integrate a better interface between the circuit board and user, to develop their second prototype. As such, the program in the first week was structured to have lectures covering soil sample preparation, measuring constituents in data collection and analysis, PDMS molding and curing, and introduction to circuits and programming (Figure 4a). The second week was structured to align with the design thinking process for one long iteration to test and build the design.

	Day 1	Day 2	Day 3	Day 4	Day 5
Session 1 10:00 – 11:00	1.1 Program Introduction	2.1 Sample Preparation	3.1 Deer Island Treatment Plant	4.1 PDMS Testing	5.1 Introduction to Programming
Session 2 13:00 – 14:30	1.2 Microfluidics	2.2 Measuring Constituents (NPK) Data Collection + Analysis	3.2 PDMS Overview and Mixing	4.2 Introduction to Circuits	5.2 Programming Workshop
Session 3 15:00 – 17:00	1.3 Microfluidics	2.3 Design Thinking and Prototyping	3.3 PDMS Molding and Curing	4.3 Circuits Workshop	5.3 Recap and Discussion
	Day 6	Day 7	Day 8	Day 9	Day 10
Session 1 10:00 – 11:00	6.1 Design Activity: Brainstorming	7.1 Building Prototype: Design and Fabrication	8.1 Prototype and Test: Integration and Fabrication	9.1 Test + Iterate: Analysis and Final Design	10.1 Presentations
Session 2 13:00 – 14:30	6.2 Ideate + Define	7.2 Building Prototype: Design and Fabrication	8.2 Prototype and Test: Integration and Fabrication	9.2 Test + Iterate: Analysis and Final Design	10.2 Presentations
Session 3 15:00 – 17:00	6.3 Ideate + Blueprint Review	7.3 Building Prototype: Design and Fabrication	8.3 Prototype and Test: Integration and Fabrication	9.3 Test + Iterate: Analysis and Final Design	10.3 Program Conclusion

Figure 4a: *Advance program schedule and topics. Workshops are in white, and lab days are in gray.*

Overall Effectiveness		**Overall Relevance**	
5.2 Programming Workshop	4.75	2.3 Design Thinking and Prototyping	4.80
2.3 Design Thinking and Prototyping	4.71	1.2 Microfluidics	4.00
3.2 PDMS Overview and Mixing	4.71	2.1 Sample Preparation	3.80
3.3 PDMS Molding and Curing	4.71	1.1 Program Introduction	3.60
4.1 PDMS Testing	4.63	2.2 Measuring Constituents (NPK) Data Collection + Analysis	3.40
5.3 Recap and Discussion	4.63	4.1 PDMS Testing	3.20
2.1 Sample Preparation	4.50	3.3 PDMS Molding and Curing	3.00
4.3 Circuits Workshop	4.50	3.2 PDMS Overview and Mixing	2.40
1.1 Program Introduction	4.43	1.1 Program Introduction	2.20
2.2 Measuring Constituents (NPK) Data Collection + Analysis	4.43	4.2 Introduction to Circuits	1.80
5.1 Introduction to Programming	4.43	4.3 Circuits Workshop	1.60
3.1 Deer Island Treatment Plant	4.40	5.1 Introduction to Programming	1.00
4.2 Introduction to Circuits	4.38	5.2 Programming Workshop	1.00
1.2 Microfluidics	4.25	3.1 Deer Island Treatment Plant	0

Figure 4b: *Student effectiveness and relevance ratings for each workshop.*

The same assessment tool was utilized in this program to measure effectiveness and relevance for the lectures (Figure 4b) as they prepared the students for the design lab and fabrication setting in the second half of the program. The most effective lectures were ones that the students had highlighted they were most excited to learn from in the program to help give new knowledge and skills to build their next prototype. One difference to highlight is the split in effectiveness between both the workshops with hands on activities for programming (5.2) and circuits (4.3) rating higher when compared to their lecture counterparts (5.1 and 4.2). When highlighting which workshops were most relevant to each of the lab days, the top 20% scoring over 75% included design thinking and prototyping, microfluidics and sample preparation highlighting the specificity of what the students were preparing to work on in the lab. The lowest relevant workshops to the task at hand with less than 20% rating were those related to circuits and programming as well as a 0 rating for the visit to the local water treatment plant. While the students appreciated those workshops for learning new skills with a high efficacy rating, the low relevancy shows these activities were not perceived as directly helpful while completing the prototype in week two.

When comparing students' confidence to the effectiveness, the effectiveness scores for material presented stayed high over 80% even when confidence dropped (1.2, 3.1, 4.2). Evaluating confidence to relevance, there are larger deltas in relevance scores than in confidence. The first workshops, 1.2-2.3 were deemed more relevant with an average of 72% than the trip to the water treatment plant (3.1) and the circuit and programming sessions (4.2-5.2)

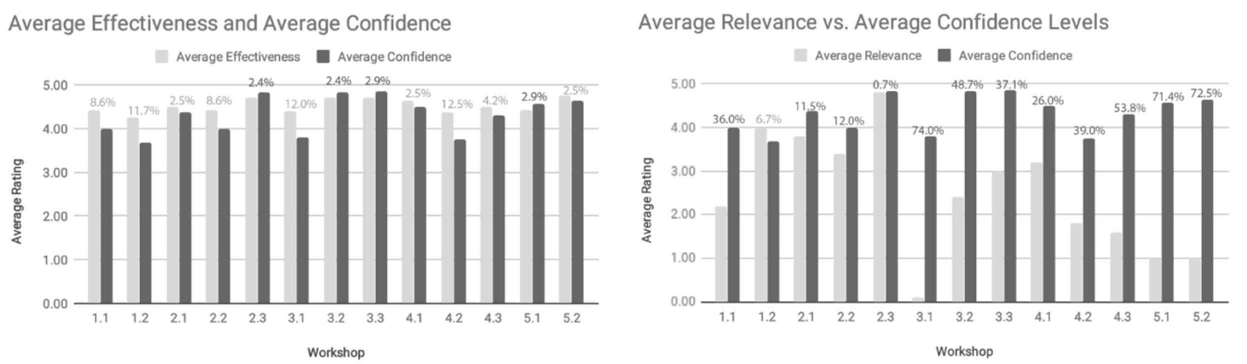

Figure 4c*: Assessment of students' level of confidence as a function of training effectiveness and topic relevance. The percentages highlight the delta between the two.*

Learning Outcomes from Both Programs

Two essential aspects of preparing engineers to be effective contributors in solving problems are effective communication and leadership. Advanced knowledge and proficiency in subject matters complement these aspects as we prepare our students to contribute to society. Each program presented the enrolled students with a set of skill-building tools that were learned through workshops and challenged them with solving complex human-centric problems. Students level of confidence in their ability to address these issues was consistently higher post the introduction of lecture and/or workshop material (Figure 5). The level of post lecture/workshop confidence was surprisingly similar between high school (Average score of 4.2/5) and undergraduate (Average score of 4.29/5) students - except for one subject area. The highest achieved confidence score is observed at the hands-on building stage, which is achieved after most in-class lectures and skill-based workshops have been delivered.

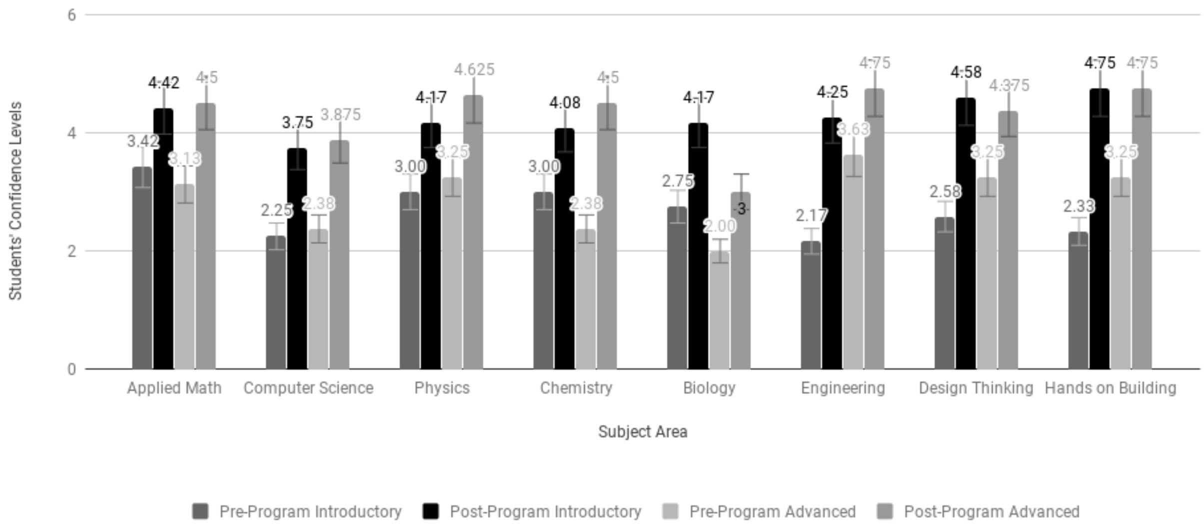

Figure 5*: Learning Outcomes - Comparing Pre and Post Average Student Confidence Across Subjects*

Conclusion

This paper describes a methodology for introducing design interventions at different scales. One at an introductory level for collegiate students and another one at a more advanced level. In both cases we introduce design as an intervention for complex and open-ended system challenges. The two programs had a diverse cohort of different ethnic background and educational backgrounds. Teaching was conducted in a supportive environment that encouraged divergent thinking in an active learning environment. Student learning and confidence increased as they developed their skills and these experiences let to more engagements after they left their programs. Students carried on some solutions in their countries which led to practical applications.

We note that for the introductory level purposes, multiple iterations and shorter design exercises were more effective learning pedagogy. For the more advanced students, a foundational series of workshops prior to prototyping enabled better learning. This work points to the importance of creating a diverse cohort; exposing the students to open ended complex challenges can be done at different levels of knowledge, and students can internalize their learning and create useable solutions when they gain enough confidence.

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