Work in Progress: Project and Design-Based Introductory Engineering Course using Arduino Kits

Dr. Demetris Geddis, Hampton University

Demetris L. Geddis is an associate professor and Chair of Electrical and Computer Engineering at Hampton University. He has extensive research experience in the areas of Integrated optoelectronics, Optics, Microelectronics, and Electromagnetics. He has worked as a Research and Design Engineer at Motorola and Bell laboratories. Also, he worked at NASA Langley Research Center as a NASA faculty fellow for the Nondestructive Evaluation Sciences Branch where he performed research in the area of optical fiber sensing for real time health monitoring of aerospace vehicles. In addition, Prof. Geddis was a Research Engineer at the Georgia Tech Research Institute where he fabricated scalable multiplexed ion traps for quantum computing applications. Current research interests and publications are in the areas of Photonics, Optoelectronics, Microelectronics, Heterogeneous thin film integration, single-fiber bi-directional communications, optical sensing, and ring lasers. Before joining Hampton University in 2017, Prof. Geddis was a faculty member at Norfolk State University for 12 years.

Dr. Brian Aufderheide , Hampton University

Dr. Brian Aufderheide is0 in Chemical Engineering at Hampton University. He completed his PhD in Chemical Engineering at Rensselaer Polytechnic Institute. His areas of expertise are in advanced control, design, and modeling of biomedical, chemical, and biological processes. He has consulted for both medical device and biotechnology companies. He was sole engineer and QC supervisor of a 40MM lb/yr custom extrusion company. He has over 15 years of experience in education developing over 25 new courses. He has supervised over 35 Industrial Design Projects. He is a returned Peace Corps Volunteer. He is dedicated in helping his students to succeed.

Mr. Herman W. Colquhoun Jr., IBM Canada Ltd.

Herman is both a designer within IBM Design Studios and a licensed Professional Engineer of Ontario (based out of Toronto, Canada) who is committed to delivering world-class products and services that drive customer adoption, loyalty and business results. He advocates an enterprise design thinking approach, which focuses on customer empathy, experimentation, design, and innovation. His experience spans brand-, web-, and product- design; information experience-, experimental- , and business-design; development consulting and business process reinvention. Herman's involvement in the area of human factors, engineering psychology, and industrial design and engineering has ranged from co-authoring journal papers and book chapters on Augmented Reality, Mixed Reality, and human-centric design to being an active speaker, facilitator, teacher and advocate for both general and minority interests in STEM, customer empathy, innovation and design.

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Demetris Geddis[1], Brian Aufderheide[1], Herman Colquhoun Jr.[2]
[1]*Hampton University, USA*
[2]*IBM Canada Ltd*

Abstract

This research is a "Work in Progress." Currently, the retention rate for engineering programs is too low. Some reasons why students change majors after the first year include student weaknesses in mathematics and physical sciences; and educators not providing enough hands-on interaction related to their selected engineering major. To help rectify the situation, the authors have revamped the Introductory Engineering course (EGR-101) to have more hands on "tinkering", a design project, and mandatory peer-lead study groups. Students received their own Arduino kits and accessories, create Arduino-based measurement tools, and use them to conduct laboratory experiments where they measure various parameters such as temperature and voltage. These experiments generate both steady-state and dynamic results that are analyzed and reported by students. In addition, students were trained in an abbreviated version of human-centered Enterprise Design Thinking adopted from IBM and given a design project that incorporated Arduino kits to be used to create design prototypes. Students had four weeks to complete the project which counted as their final. This approach aimed to demonstrate engineering principles in action so that students can make a better-informed major and career decision. Overall, preliminary results show that students in the course are more engaged and feel they have a clearer sense of engineering.

Keywords

Introductory Engineering Course, Undergraduate Engineering, Arduino Kits, Human Centered Design Enterprise Design Thinking

Introduction

The global workforce demand for highly competent engineers with good communication, problem-solving, and critical thinking skills continues to sky-rocket [1]. To alleviate this issue and increase the number of well-equipped engineers, the retention rate of 47% degree attainment in five years must be addressed [2]. The "Sage on the Stage" lecture-style approach to teaching has not been effective and is estimated to be the cause of 27% of the attrition, [3]. Project-based learning is on the rise. This student-centered approach allows learners to actively explore problems and challenges, acquire knowledge, and get a good sense of their abilities. Project-based learning is ideal for introducing students to the profession of engineering and for allowing students to be tinkerers. A tinkerer is an "unskillful mender" and tinkering is "to repair, adjust, or work with something in an unskilled or experimental manner" [4]. The objective is to have students who start as "unskillful mender" realize, through hands on activities, that they have the capability to do quite a lot while learning and gaining "skills". Design is another important aspect of engineering that is enabled by project-based learning. Projects devised from real world problems may be used to teach students how to think critically and humanistically about possible solutions. The goal is to have students use a human-centered design thinking approach when problem-solving or iterating with a prototype. Arduino kits have been selected as the preferred tool for problem-based/design-based instruction because they are economical and a very flexible prototype medium. The first iteration of research conducted by the authors using Arduino kits for project-based instruction had several merits not discussed here, but fell short in data analysis and human-centered design [5]. This research addresses the following question: will a project-based learning approach including tinkering, design, and Arduino kit-based prototyping, lead to better retention of our underclass engineers?

The project-based learning approach was implemented in an Introduction to Engineering course. However, freshmen engineering students may decide that engineering is not for them because of the lack of success in foundational math and science courses, which has been found to be 28% of the cause the attrition [3]. Therefore, an ancillary research question is: Can mandatory study groups formed in an introductory engineering course, help students succeed in other gateway classes? The results to the two research questions are reported with links to supporting videos.

An Introduction to Human Centered Design

In order to discuss design thinking and, by extension, IBM Enterprise Design Thinking (EDT) - paraphrased as human-centered design at scale (and speed) - we must first ground ourselves in the definition of general human-centered design (HCD) and the root meaning of design. A design is defined as the purpose, planning, or intention that exists behind an action, fact, or material object. In and of itself, design is neither good nor bad until it is given purpose. Furthermore, "Human-centered design is an approach to interactive systems development that aims to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors/ergonomics, usability knowledge, and techniques. This approach enhances effectiveness and efficiency, improves human well-being, user satisfaction, accessibility and sustainability; and counteracts possible adverse effects of use on human health, safety and performance" [6]. As, Don Norman, renowned researcher, author, UX entrepreneur, and professor stated: "Designers resist the temptation to jump immediately to a solution to the stated problem ... They don't try to search for a solution until they have determined the real problem, and even then, instead of solving that problem, they stop to consider a wide range of potential solutions. Only then will they finally converge upon their proposal. This process is called 'Design Thinking' [7, 8]. The general "process" of design thinking can be extended with the "framework" of IBM EDT. Both methods are based in HCD but the latter resulting in an engineering education approach that develops skills applicable to efficiently and effectively solving industry problems while enforcing human-centered focus. The students were asked to solve a given problem using an EDT approach and prototype one of their potential solutions with an Arduino kit.

Methodology

1. Instruction on Use of Arduinos

All students enrolled in the Project-Based Introduction to Engineering course were issued their own Arduino kit so they could do homework and laboratory assignments outside of the classroom and tinker at their leisure. Inaugural classes were dedicated to discussing Arduinos kits' design and function as well as the breadboard; as it is often used in conjunction with the Arduino for prototyping circuitry. Pre-assignment generalizations about the circuitry and setup were given with more in-depth dialog following completion of the task.

2. Arduino Configured as a Measurement Tool

Arduino kit utilization has been so educationally impactful because it has enabled students to "learn by doing" through building simple projects. The usefulness and learning objectives of these projects can be extended if it results in the creation of a tool. In addition to building "blinking lights" circuits that are captivating, students built sensory-based thermometers and the voltmeters. These tools were then used to complete three laboratory assignments.

Laboratory 1: Temperature Sensing Lab

Objective: Use a precision temperature sensor such as the TMP36 to measure the ambient temperature and learn how to collect, model, analyze and report data.

This was the first laboratory assignment for the students. At this point in the semester, students were familiar with the breadboard, basic circuits and uploading code to the microcontroller. They were given the schematic and the required code. After building the temperature sensing circuit and uploading the code to the microcontroller, students used the tool to measure varying temperatures under different conditions: cold using an ice pack and heat with a hair dryer. The temperatures were recorded using their computer and the Arduino's IDE serial monitor. Students were then required to plot and fit the data using Microsoft Excel. Students were asked to see if noise levels differed depending on temperature and were required to determine if the recorded data was linear or exponential. A formal laboratory report was written and submitted.

Laboratory 2: Voltage Sensing Lab

Objective: Construct an Arduino-based voltmeter with an LCD to measure voltage and learn basic circuit analysis such as Ohm's law, voltage division, and RC circuit dynamics.

Students constructed an Arduino-based voltmeter. The requisite code was uploaded to the microcontroller. To check for accuracy of their new tool, students measure a 5V voltage source. Following this step, student built a series circuit with three resistors and the 5V source. They measured and recorded the voltage drop across each resistor. After recording the voltage measurement across resistor 1, resistor 2 and resistor 3, and all three resistors, the students plotted the results and found a fit for the data.

Next, the students, placed a resistor and capacitor in parallel with the 5V source. After removing the source voltage, the students recorded the voltage using the Ardinuo's IDE Serial Monitor. Once again, the exponential data was plotted and fitted using Excel including the time constant of the RC circuit.

Laboratory 3: Voltaic Cell Lab

Objective: Review batteries/electro-voltaic cells and their chemistry, and how it relates to chemical engineering and electrical engineering.

For this laboratory experiment, students used various chemicals and metals to construct voltaic cells. The first voltaic cell was created using copper and zinc as the electrodes along with copper sulfate and zinc sulfate solutions. The two solutions were separated by a porous cup that also served as a salt bridge. The Arduino-based voltmeter constructed in laboratory 2 was used to measure the cell voltage. After recoding the data and analyzing the results theoretically, using the Nernst equations, students replaced the sulfate solutions with Acetic Acid (vinegar) and built other cells by varying the metal combinations. The available metals included: iron, tin, nickel, zinc, aluminum, and copper.

3. Study Groups

The Introduction to Engineering course at Hampton has the traditional goal of exposing students to the technical aspects of the profession of Engineering. In addition to stressing the technical side, the importance of teamwork for academic success was emphasized through forming mandatory Study Groups. Students were placed in groups of six to eight. They were required to meet at least once a week to study calculus, physics, or chemistry for one to two hours. The Study Groups were led by NSF funded Hampton-Brandeis Partnership for Research and Education in Materials (PREM) program scholars.

4. IBM Enterprise Design Thinking

Enterprise Design Thinking (EDT) is the framework IBM Design uses to collaborate, align teams and form intent to solve users' problems — all while improving customer experiences at the speed and scale the modern enterprise demands. IBM designers focus on the outcomes that delight users and deliver increased value to meet their business goals. The synergy between a diverse mix of design, engineering, and business acumen is necessary in driving success and sustainability for any product or service. By establishing empathy with the user, designers are able to work toward outcomes that meet those needs with better success. This framework enhances user-centered approach known as "design thinking". In industry, it enables designers and others within enterprise level organizations to address a wide range of complex business and social issues. In education, it enables students to learn from a practical approach before they become design candidates; and bridge a skills gap that IBM is currently witnessing exists with graduates coming from design related programs.

Business and social solutions are derived by first understanding the problem and identifying the most impacted needs (emotionally- and efficiency-based) that a problem creates. EDT encompasses three principles: a focus on user outcomes, diverse empowered teams, and restless reinvention [9]. These principles that mirror the DNA of Agile methodology taught to engineers – clarity of outcomes, self-directed teams, iteration and learning. Success is measured by how well we fulfill our users' needs – the user outcomes – not by features and functions. Functionally-, ethically- and otherwise diverse teams generate more ideas than homogeneous ones, increasing breakthrough opportunities. While, considering that every stage of design is a prototype from a storied drawing to in-market solutions; iteration empowers the application of new thinking to seemingly stale issues. The keys to scaling design thinking to complex problems and complex teams involve aligning on a common understanding of the most important and most impactful user outcomes to achieve (called Hills); and bringing the team and stakeholders into a loop of restless reinvention where they reflect on work in a safe, inclusive space by executing Playbacks at every stage of the loop (i.e., observe, reflect, and make) to maintain team alignment and focus – a skill which also benefits group projects. Finally, collaboration with real users increases the speed of convergence from assumptions to a true understanding of the user's reality. Involving users is key in achieving this understanding and delivering client outcomes that lead to business success.

a. IBM Visit and Guidance

Hampton University's IBM Academic Design Focal, Herman Colquhoun Jr., visited and delivered a keynote lecture to the EGR-101 class. The keynote consisted of outlining a path and relationship between engineering and design consisting of personal and professional anecdotes ranging from positions in human factors engineering research to design leadership. His talk drew the connection between Engineering curriculum and it's application to industry. He also reviewed the responsibilities of engineers in recognizing the influence of disruptive technology designs; the dilemmas created by the onslaught of rapidly advancing AI technologies; and the complexities of the ethics and bias associated with both that can only be resolved by carefully thought out and deliberate design (with EDT).

Constructive guidance was provided, walking the students through the concepts of restless reinvention. Methods for observing sponsor users including journaling, structured interviews, audio/video recordings, and ethnographic observation and their usage scenarios were discussed. The utility of tools for the reflection of human behaviors and needs in the course of empathetic design was also covered to inform the students on practical methods to incorporate in their design projects to ensure they address real world problems. These tools include empathy maps, persona development and As-Is scenario mapping. The lesson culminated with a review of the "make" methods to iteratively ideate and create visualizations to communicate their solutions including ideation, prioritization, storyboarding, and prototyping. During the course of applying their lessons to the practicum and continued EDT education on-line, 77% of the students successfully completed the online requirements to earn their IBM EDT Practitioner badge.

b. Hampton University Implementation

Our goal was for the students to use EDT, and have the student teams develop solutions that they would prototype using Arduino kits with additional sensors. Students could then build prototypes as part of their final project. Along these lines, we crafted the following problem statement given to the students: "Design a better way for Ted, a blind student at Hampton University, to navigate through populated areas without using a stick or service dog." This short-circuiting of the EDT framework was done to save one step in the overall design task flow.

All in-class exercises were time-boxed and required class participation, discussion, note-writing, and short organization using large sheets of paper covering each exercise in special diagrams. The exercises were modeled after many of the activities created to support radical collaboration found in the IBM Design Thinking Field Guide (version 3.5)[4] Deviations from the recommended procedures are outlined and attached in Appendix A. The completed exercises were as follows:

1. Supplies and Design Activity set-up (20 minutes)
2. Mock user interview (15 minutes)

3. Empathy Mapping (10 minutes)
4. As-Is Scenario Map (10 minutes)
5. Ideation with Vignettes (12 minutes)
6. Prioritization (10 minutes)
7. Storyboarding (3 days)
8. Prototype – Playback 0 (1.5 weeks to prepare 10 minute playback with prototype)

Results and Discussion

Students first started using the Arduinos by following set instructions building circuits. The student's submission was uploading videos where they introduced themselves, showed uploaded code and circuit working. Standard submissions can be seen here and here. Students working through the first two circuits step by step for Circuit 1 and Circuit 2. One student added text and music to both Circuit 1 Extra and Circuit 2 Extra. In another case, a curious student, unguided by instructors, modified the Arduino code. In general, the students enjoyed making videos and submitting them as part of their work.

The Arduino labs ran smoother than the previous year by increasing the length to the lab period from one hour to two hours [5]. Initially students struggled with building the more complex circuits required, and debugging them. Retrieving data using the Arduino kit was relatively simple; however, data retrieval during resistor capacitor discharge was more challenging as students often had to add more resistors to increase the time constant of the voltage drop. It was educational to determine the selection of resistors required to collect the desired number of data points over a time period. The difficulty was in analyzing the data using Excel and compiling the hand calculations. The grades for the labs were a broad range from 50 to 96 with averages in the low to mid 80's and standard deviation of 7 to 11. Data analysis and write up were where most points were lost.

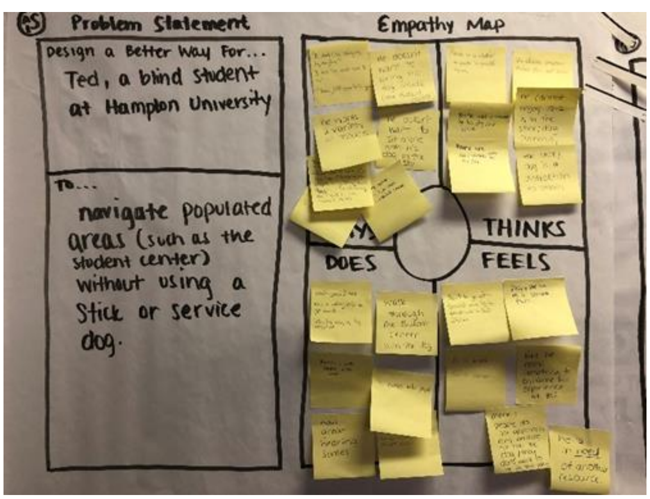

Fig. 1. Empathy Map created by students.

For the final project, the students started a bit slow with day one of the IBM Enterprise Design Thinking exercise. Students who had gone through the exercise before as facilitators were available to help get the students started, and all groups finished the day strongly. All the groups completed the IBM Enterprise Design Thinking exercise with more than adequate work and thought on each step, and earned high scores - greater than 90% (submitted Empathy Map in Fig. 1).

Due to the nature of the prototype medium, all of the groups selected wearable designs, shoes, bracelet, cap, belt, and coat, that used ultrasonic transducer sensors couple with sound to tell "Ted" if an object was close by or not. The Storyboard (see fig. 2) and resulting video for each group initially had some push back from the students on how difficult it would be to do in the three days allotted. Yet all of them did an outstanding job as seen here for a coat, a belt, a bracelet, and shoes. The quality of the videos was impressive as well as the effort the students put into them. The marks for the Storyboard and video presentation ranged from a low of 80 to a high of 100 with an average of 95.2 percent (i.e. grading scale, A- is 90 – 92, A is 93 – 97, and A+ is 98 – 100). It was great to see how high the participation was in each video by all team members. Buoyed by the success of their storyboard videos, students worked hard to get a working prototype. Students modified code and circuits for an ultrasonic transducer sensor with an Arduino kit so that auditory alert for proximity to be louder and/or adopt a different pitch. They quickly learned that the Arduino kits can use an external power source and do not require connection to a PC to be operated.

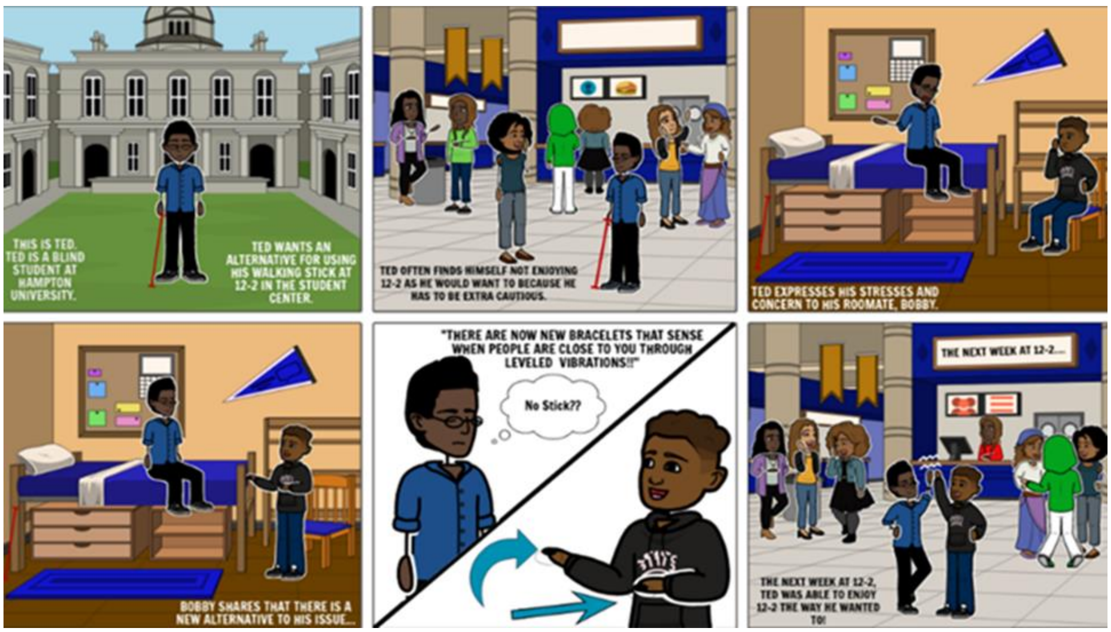

Fig. 2 Storyboard created by students during design process.

Fig. 3. Prototypes constructed by Hampton University engineering students

They experimented with the ultrasonic transducer sensor and tested its ability to work on detecting people or walls. The groups purchased clothing items such as shoes, bracelets, backpacks, and tossle cap which they then modified to embed sensors, wires, and speakers. All groups had a working prototype ready for their final presentation (see fig. 3). Overall, the final presentation marks ranged from an 80 to 100 with an average of 90.9 percent.

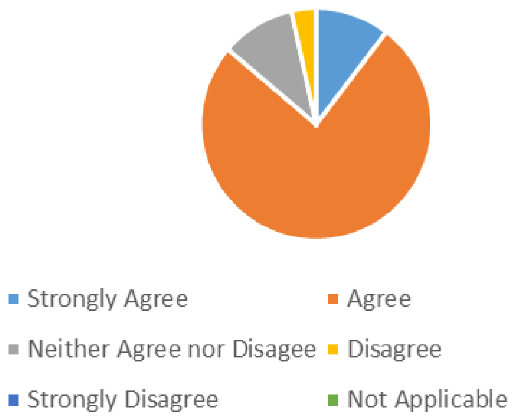

Fig. 4 Did this course improve your understanding of what engineering entails?

Twenty-nine students completed a 5 Likert question survey about the revamped project and design-based introduction to engineering course. Eighty-six percent (86.2%) of the students surveyed strongly agreed or agreed that the course improved their understanding about engineering (see fig. 4). Sixty-two percent (62.1%) of the students indicated that the Arduino projects increased their motivation in the class. Although, 77% of students had met the criteria and completed the online requirements to obtain their IBM EDT Practitioner badge; only sixty-nine percent (68.9%) of the students were confident (i.e., agree and strongly agree) that they now understand design thinking. The authors feel that this gap exists and could be lessened by addressing some shortcomings in the instruction. The students could have benefited with more frequent exposure to design thinking experts; increased time to iterate through the framework; and by being asked to more accurately report on individual project contributions. Sixty-six percent (65.5%) felt that the formation of mandatory study groups was helpful. Fifty-nine percent (58.6%) of the students are confident that they have chosen the correct major based on what they have learned in the course. However, 34.5% selected Neither Agree nor Disagree and 6.9% selected Disagree or Strongly Disagree about their confidence in being an engineering major.

Conclusions and Future Work

After two iterations of using problem based learning approach with Arduino kits in our Introduction to Engineering course the following conclusions can be made: students felt strongly that this approach is more engaging and that they have a better understanding of what engineering entails. Although it is trending that retention is higher with this approach, the statistical data sets are too small to be conclusive. Overall, the biggest challenge is the very uneven foundational skills of the students especially in mathematics. What can be frustrating is the number of help sessions in all introductory STEM classes, and yet it seems only the very best students consistently take advantage of these opportunities. The study groups being mandatory and being led by other students help but by how much is not clear yet. The course was much more rigorous with more data analysis and using Excel. Three Arduino labs were given with additional one using pH probe for Honors Students. With better coordination and preparation, we should be able to add one more lab next year. Students took very well to the human centered design work with IBM, and will be done again next year. However, the instructors will consider initiating the final project one week earlier, and if possible involve real users in the process for one or more interviews to validate any assumptions and correct misconceptions. Incorporating video as part of the submission by the students greatly enhanced the quality of the student work. Instructors generating videos for a flipped classroom in the areas of units and conversions and Excel data analysis would assist the students greatly. Another suggestion would be to leverage the past student videos for the cohort homework circuit to assist next class in building their first Arduino kit.

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APPENDIX A:

Hampton University Implementation of IBM Enterprise Design Thinking

1. Organization of Exercises: introduction of upper class students assisting the first exercises; purpose of the exercises; expectations of the instructors; answering any questions before beginning; handing out materials; drawing diagrams on flip charts that will later be used to place and organize sticky notes and stickers for selections of ideas, etc. (20 min).

2. Introduction of Stakeholder, Ted, a blind student who finds it difficult to navigate student events which have a large number of people. Instructor plays Ted and gets interviewed by students. Students are allowed to ask Ted questions prior to each exercise. (15 min)

3. Empathy Map: Says...Thinks… Does… Feels. Individually (5 min) each student writes at least two sticky notes for each category. The focus is on Ted: students try to put themselves in his shoes. The goal is to write as many thoughts as possible, one to each sticky note. Group (5 min) discusses and places similar thoughts on a large empathy map diagram with one quadrant for each category. Identify Ted's pain points: What does he value? How is he feeling? What is he thinking? Stress that this is the key exercise of all the ones to be done.

4. As-is Scenario Map. This exercise outlines the scenario for Ted. Ted attends an event where he feels uncomfortable and/or is using his walking stick. First start this exercise as a Team to outline a scenario with one sticky note for each phase of Ted's experience; steps are placed on the Scenario Map representing a column (5 min.). Second as Individuals write sticky notes for what Ted is Doing, Thinking and Feeling during each step, and place these so first row is Doing, second is Thinking and third is Feeling (5 min.). At this point, no solutions are being discussed. Groups are really digging into what Ted is dealing with.

5. Ideation. Individuals (5 min) generate at least 3 ideas to help Ted, one idea for each sticky note. We added another 2 minutes since students wanted more time, and another 5 minutes for "outlandish" ideas. Note that this is the first time in the exercise that engineering design solutions are contemplated. The focus is on the Stakeholder, and only when having a better understanding of him/her and the situation does one start to actually consider engineering solutions.

6. Prioritization Grid. Students place all ideas on prioritization grid. Grid has y-axis Impact and x-axis Feasibility. Each student places her/his ideas on the prioritization grid (5 min.). Students get four stickers to vote for what they consider the team's best ideas. (5 min).

Exercises completed by students as assignments outside of class and then presented to whole class:

7. Storyboard and video of storyboard presented to class. Students were given 3 days to complete the assignment. As an example and for inspiration, we showed the class the storyboard and video done by the winning design team in 2019 AMIE Design Conference at BEYA. Two 2019 team members answered any questions the students had concerning the exercises.

8. Final 10 minute presentations with working prototype. Students were given 1.5 weeks to complete the assignment.