Using Human-Centered Design to Drive Project-Based Learning in a High School Summer STEM Course (Evaluation)

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Abstract

This paper presents a case study describing improvements made to an existing makerspace high school summer outreach course, by using survey data to evaluate the effectiveness of adding Human Centered Design (HCD) into a project-based inventorship curriculum. An existing high school summer Makerspace course was adapted to emphasize HCD as a driving force for real-world engineering educational experiences for students. Makerspace students were enrolled for 120 hours over six weeks, where they learned about design and prototyping through workshops and a creative invention process. Teams of three to four students identified a problem statement, created a working prototype, collected user feedback, and refined their invention to achieve a minimum viable product. Student teams used HCD and customer validation in order to develop a product with specific customers in mind and acquired feedback by interviewing users. The teaching team used a combination of inquiry, problem, and project-based learning pedagogies to reinforce student learning, often on a case-by-case basis in order to meet the demands of each project. The Makerspace was one of ten sections in the overall summer STEM program and concluded with demonstrations and a formal presentation to all other sections of the program. Entry and exit surveys were administered to the students to collect their demographic information, self-assessments of their skills and interest in engineering. The effectiveness of the Makerspace teaching model to the spur student learning of engineering skills was validated by student growth and confidence in manufacturing, electronics, entrepreneurship, and design skills.

Introduction

High school summer Science, Technology, Engineering and Math (STEM) programs are out-of-school opportunities for students to participate in learning opportunities they may not have at their schools. Existing programs that teach STEM concepts may be held onsite at a college or university and with opportunities for high school students to engage with college-level educators, learning pedagogies, educational tools, and career pathways. The Cooper Union is a college located in New York City that has been delivering STEM programming in the summer for over 30 years. The high school summer STEM program offered by Cooper Union has various sections that have traditionally been instructed by professors specializing in one of the four engineering majors at the college: chemical, civil, electrical, and mechanical engineering. Each year, the program lasted six weeks and consisted of 120 hours of informal project-based learning, with each section grounded in different engineering challenges.

Starting in 2015, the institution began to offer a new section called the "Makerspace" section in order to address the demand for modern technologies and skills sets, such as rapid prototyping, microcontroller projects, 3D printing, laser cutting, and CAD. In 2018, the Makerspace section was offered as an option out of ten sections at the Summer STEM program and differed from previous iterations of the curriculum because of the additional emphasis of Human Centered Design (HCD) to guide each student team's design process. There are three primary goals in this document to evaluate the 2018 Makerspace: 1) identifying how the curriculum fits within existing pedagogy, 2) depicting the organizational and teaching methods and 3) analyzing survey methodology and responses to suggest trends and potential improvements.

Background/Literature Review

The 2018 Makerspace section combined various design processes to reinforce the Project-Based Learning curriculum where student teams invented projects to solve meaningful problems. The Engineering Design Process has been heavily emphasized across all project-based sections of summer STEM program and its use is typical of the engineering classes at Cooper Union where this program was offered. Since the inception of the Makerspace in 2015, Problem-Based Learning has also been used within engineering design to reinforce student understanding of problem-solving for the specific customers who would use their invention. The new emphasis of HCD in 2018 emphasized Inquiry-Based Learning in the curriculum, as students learned to ask their audience meaningful questions to acquire new perspectives that shape their work while iterating through the stages of engineering design.

Engineering Design Process

The Accreditation Board for Engineering and Technology defines the Engineering Design Process as "the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs"[1]. It appears as interpretations that vary in the number of stages, emphasis on stages, and has been portrayed as a linear and cyclical. One variation is the Atman model, a six-stage linear model that includes: 1) problem definition, 2) gather information, 3) generate alternative solutions, 4) analysis/evaluation, 5) selection and 6) implementation/communication[2]. For projects that have longer time constraints, the engineering process may be cyclical in nature because of the opportunity for student engineers to improve their design by cycling back to an earlier stage. The NASA Engineering Science and Technology model is a six-stage cyclical design process featuring the stages: 1) Ask, 2) Imagine, 3) Plan, 4) Create, 5) Test and 6) Improve [3].

Students using the Atman or NASA model typically begin by identifying problems and constraints to design around. In both, they collect information, consider design alternatives and finally create and test a particular solution. The Makerspace also implemented differences between the two engineering design processes into the curriculum. The additional emphasis on communication with product users within the Atman model was applied when student teams communicated with users to improve their designs. The cyclical nature of the NASA model was employed when student teams performed major design iterations in each week of their projects.

Human Centered Design / Design Thinking

Like the NASA model, HCD is also cyclical in nature with emphasis on iterative product design. HCD also has a particular emphasis on the communication of ideas, like the "implementation/ communication" stage of the Atman model. The phrase HCD was popularized by the nonprofit design organization IDEO since 2009 and is also referred to as Design Thinking [4]. Since then, literature summarizes and assesses instances of its application [5]. HCD emphasizes the communication between designers and the people they design for, which often results in improved user satisfaction and lower developmental costs[6]. Designers use customer interviews as a core activity to develop an emotional understanding of the users of the design and their stories [7]. HCD is often associated with finding solutions for problems in social, economic, and resource distribution settings. The cyclical nature and stages of HCD product development can also be applied to engineering courses. In these cases, the engineering design process becomes a subset of HCD, by using human interactions as part of the process of developing, testing, and evaluating ideas [8].

Entrepreneurship / Product-Market Fit

An entrepreneurial perspective on customer segments and value propositions help designers recognize that solutions must be designed around user requirements and shares this common goal with HCD. Existing works such as *Business Model Generation* [9] defines the Business Model Canvas as a tool to help startups visualize their business model and interconnected components. The product-market fit is typically the first part of the business model to be developed and consists of the Customer Segment and Value Proposition components. The value propositions of a product or service create benefits or eliminate pain points for its users. The customer segments are users who benefit from the value propositions through the innovative product and often include the people with purchasing power in addition to the end user. Proper identification of these two components designers understand design constraints and create products that are more impactful toward specific audiences. This product market fit is often refined by data collected from interviews with potential customers. Makerspace students are responsible for understanding the product-market fit of their inventions and using interviews to improve their designs.

Inquiry, Problem, and Project Based Learning

Existing works compare the different pedagogies of Inquiry-Based Learning, Problem-Based Learning and Project-Based Learning [10]-[12]. Each learning pedagogy also has similarities that allow them to easily transition or overlap, as described by Oguz-Unver and Arabacioglu [10].

Inquiry-Based Learning presents opportunities for students to acquire knowledge by asking questions to exercise observation skills and deductive reasoning [10]. Joseph Schwab, a pioneer of this pedagogy, recommends that students practice inquiry in laboratory instruction before being presented with large amounts of facts through formal explanation [13]. He considers it as an effective way to improve knowledge transference in comparison to traditional laboratory instruction that only offers a formal explanation. Students do not need extensive knowledge of the subject matter because they learn about it by asking their target users and teachers. Makerspace students used inquiry through HCD to ask questions and used deductive reasoning in order to gain knowledge about the people for whom they were designing a product for.

Problem-Based Learning focuses on real and meaningful problems to reinforce student learning. It is similar to inquiry-based learning because on the emphasis on a curiosity-driven learning process, considering Savery's description of John Dewey's work on learning pedagogies [14]. It is also noted by Oguz-Unver that problem-based learning often starts with inquiry. Early applications were seen in medical schools in order to show the relevance of medical subjects within meaningful problems in real settings [10]. Makerspace students applied real-world problem solving with an entrepreneurship context as they developed innovations based on their curiosity of a meaningful problem that real consumers face. Students were more intrinsically motivated to problem-solve because they were developing a practical solution for a real problem that existed outside of the classroom.

Project-Based Learning requires prior knowledge and skills in order to develop a solution to a real-world problem. However, a key distinction of this pedagogy is the desired outcome for a tangible product that is produced over a long period of time with hands-on work [10]. Examples include engineering projects that require many weeks and use hands-on tools and skills to design, build, refine, and deploy a solution. Makerspace students used iterative design processes, like the HCD and engineering design to exercise their design skills and refine their creations until they reached a final product.

The 2015-2018 Makerspace sections have been primarily project-based experiences for students to exercise inventorship by following engineering design models. The 2018 teaching team had students use HCD to develop inventions with real-world involvement through inquiry and problem-based learning objectives instead of inventing for theoretical problems. As a result, students learned more independently from teacher lectures and instructions and produced inventions that solved problems more meaningfully.

Program Development

Makerspace is a six-week high school engineering curriculum and part of the Summer STEM program at Cooper Union. The core goals for the program remained the same as the first time Makerspace was offered, while a variety of teaching approaches were used. Each year, a cohort of students learned engineering skills by identifying a problem, then designing and building a solution. The teaching team consisting of an instructor and 3 to 4 teaching assistants (TAs) who were undergraduate college students also varied between each year and adapted the curriculum to include new technology and materials. Students typically learned to use rapid prototyping machines such as laser engravers, 3D printers, and shop tools. Students also used tools such as Computer Aided Design (CAD) software, microcontrollers, and computer programming languages. In addition to engineering skills, program-wide activities included: college and career planning seminars, technical writing and presentation workshops, field trips and guest speakers.

Makerspace 2015: The Cooper Union model

In the first year of the program, the primary goal was to expose high school students to engineering design process used in first year undergraduate courses and provide an opportunity for students to practice skills by developing a project. The first iteration of this curriculum at Cooper Union was evaluated by Bill and Skolnick [15]. It describes the resources used, instructional methods, examples of student work and survey questions and results. Students teams were challenged to invent a consumer product inspired by a combination of student and teacher ideas. They were expected to identify problems they found personally meaningful by researching existing technologies and create a solution that was unique enough to be patentable.

Makerspace 2016-2017: Inventorship and Patents

The 2016 and 2017 Makerspace also engineered consumer products but went further in the inventor process to understand patenting and write a provisional utility patent application. To ensure that they were not infringing on existing intellectual property, students frequently researched existing solutions and refined their designs based on what had not already been released to the public. Mentors with patenting experience, such as a patent lawyer, coached students on how to file a provisional patent application. This created a unique opportunity not offered within other pre-college programs in the local area.

However, student teams struggled to finish both their provisional patent applications and their projects within the six weeks in both years. The teaching teams were also concerned that students did not experience enough opportunity in design and prototyping due to the additional workload in patent documentation. As a result, this provisional patent element was removed after 2017 to prioritize student mastery of skills in design and prototype rather than documentation.

Makerspace 2018: Human Centered Design
HCD was implemented in 2018 as a method to spur designers to deeply understand the needs of potential end-users by conducting interviews. Students were introduced to the idea of developing "user empathy", that is, an understanding of the habits, lifestyles, and activities of the users whom they are designing for. Student teams typically discovered a user story to retell to during presentations to communicate their motivations. Gathering data through interviews supplemented the testing phase of the engineering design process and helped students arrive at solutions that were more desirable and useful for end-users.

Student application of HCD evolved as teams were coached with examples of how to ask meaningful questions to the potential users of their products. This included the end user as a part of the iterative process and reinforced the ideation as student teams co-created their products with users. The focus shifted toward the process of understanding and solving a meaningful problem instead of inventing something that did not exist in the past by using newly learned engineering tools. This helped students learn to think and work more independently of their instructor. Some products that resulted were even less complex than previous years since students learned that users did not care about complicated and high-tech solutions, but wanted reliability and cost efficiency. This change also reinforced student self-efficacy because they did not need to learn overly challenging design and prototyping skills beyond first-year engineering college coursework in order to solve conceptual problems.

Instructional Methods
Program Objectives
The goal of the 2018 Summer STEM Makerspace was to provide an engineering educational experience that used design methods, design and prototyping tools, and college mentorship to develop student-selected invention projects. Unlike previous years, learning objectives were divided into four categories: manufacturing, electronics, entrepreneurship, and design.

In the first two weeks, the teaching team used in-class workshops and activities to equip students with a basic understanding of the available tools in the college setting, such as rapid prototyping, 3D CAD, Arduino microcontrollers and programming, 3D printing, laser cutting, and traditional manufacturing tools. Students were also exposed to weekly one-hour lectures to broaden their expectations of-of college engineering beyond the first year of typical engineering studies. Examples included introductions to topics such as sorting algorithms, Python programming, and control systems. At the end of the first week, students were organized into teams of three to four to work on an invention of their choice for the rest of the program. The final team projects are described in Table 1, which summarizes each project, activities, and components used.

Table 1: Makerspace Student Team Final Projects

Project Name	Key Activities	Electronic Components	Other Hardware	Instructor summary of the project
Pageflip	Circuitry, Coding, 3D printing	Arduino, stepper, DC motors, tactile button switch	1/4" wood dowel, rubber, CYA glue	The Pageflip is a device that clamps onto a music stand and helps musicians turn music sheets that have been bound together in a booklet while both hands are preoccupied with playing an instrument by pressing a pedal. The device features a rubber wheel that which lifts a single page, and a sweeping mechanism that rotates to turn the lifted page.
Auto Turner	Circuitry, Coding, 3D printing, Laser Cutting	Arduino, stepper motor, DC motors, tactile button switch	1/4" wooden dowel, rubber sheets, CYA	The Auto Turner helps musicians turn loose music sheets that are not bound together in a book, with the press of a pedal. Since the pages are individual sheets of paper, the mechanism utilized for this design involves paper gripper mechanism comprised of wheels powered by one motor, which grab the edge of a page. This gripper mechanism is mounted on a rotating arm so that after the arm turns and flips the page, with wheels on the gripper spin in reverse to release the page. The entire device is mounted on its own backboard, which can be placed on top of any music stand.
Find!	Circuitry, Coding, 3D CAD, 3D printing	Arduino, LED's, Piezo Buzzers, Radio Frequency Transmitters	Double sided adhesive tape	"Find!" uses radio frequency in order to send a signal from an RF transmitter to an RF receiver, which will then make noise and turn on an LED to alert the user of the location. The improvement is that the device will be a standalone system that it does not require an expense coming from a smartphone, GPS or Bluetooth technology.
Brush Saver	Circuitry, Coding, 3D printing, Laser Cutting,	Arduino, DC motor w/ breakout board, potentiometer, LCD Display	Spring (for telescoping function), hot glue, CYA	The Brush Saver is a battery powered, motorized device which can adjust to hold and spin paintbrushes of various sizes in a small tank of water. The solution intends to help painters save time from having to clean brushes manually, while also preventing typical damage done to brush bristles in the typical wiping and washing process. The 2nd version of the Brush Saver also features an LCD Display which counts the time the brush has been spinning.
Grip Glove	Circuitry, Coding, 3D printing, Laser Cutting, Sewing	Arduino, Stepper motor w/ breakout board	Fishing line, Rubber coated work gloves, hot glue	The Grip Glove is a mechanical glove with a winch system designed to increase hand mobility, reduce muscle fatigue and injury from heavy lifting. The glove features 3D printed plates that conform to the shape of the back of a hand, with a line running through the grooves built into the plates on the glove, which are contracted or extended with the help of a stepper motor acting as a winch.

Each team's invention process was driven by a combination of HCD, the Engineering Design Process, and understanding of the product market fit by incorporating inquiry and problem-based pedagogies into a project-based engineering framework. Since the design process heavily involved the end users of the inventions as well as student curiosity, the teaching team had to work flexibly to guide student learning.

Role of the Teaching Team

In order to proactively respond to student learning goals, the 2018 Makerspace section teaching team consisted of one instructor and three TAs of varying capabilities. TAs were selected from a pool of applicants based on their aptitude in manufacturing, electronics, entrepreneurship, and design skills, and their ability to facilitate, mentor, and guide student learning. The following is an example of a distribution of TA skills. One TA may have an electrical engineering background to assist in circuitry, programming, and microcontrollers. A second TA may be experienced in rapid prototyping with proficiency in operating and maintaining 3D printers. A third TA may be well-versed in design and manufacturing methods, with a background of inventorship and provisional patenting. The role of the teaching team adjusted according to student need during the program. In the first week, the teaching team had more responsibility to instruct students about preliminary knowledge and facts through lessons. As student projects grew to rely more on student curiosity and customer feedback, the teaching team reoriented to serve as guides and mentors to facilitate each student team in learning advanced manufacturing, electronics, programming, and design skills in a case-by-case basis.

Ideation

Various ideation activities were incorporated to build and reinforce each student's foundation in generating and developing ideas. Examples of failed products were mentioned to show the problem of over-designing and relying too much on high-tech solutions because they are vulnerable to low levels of user satisfaction. The inclusion of Problem-Based Learning defined a scope that required meaningful and real-world problem statements before developing a solution. The activities described in this section were often based on the initial stages of the engineering design process, such as the "problem definition" and "gather information" stages of the Atman model, or the "Ask" and "Imagine" stages of the NASA model. The teaching team arranged for students to work in different groups for each of the three ideation workshops, with a five-minute team presentation at the end of each one.

In the first ideation workshop, students identified a problem that was meaningful to them and brainstormed with each other to develop problems using the skills they had before entering the program. In the second workshop, students examined existing consumer feedback on educational toys in order to develop an advancement. Although HCD typically uses in-person interviews to collect feedback, the method of analyzing product reviews was a beginner-friendly step to identify existing problems before doing real interviews. In preparation for the third ideation workshop, students were introduced to the product-market fit of the Business Model Canvas to help them identify meaningful problems for which they could design a wearable device.

At the end of the first week, students gave a 90-second pitch on an idea they would like to develop in a team of three to four for the remainder of the program. The individual student results of the pitches before team assignments were summarized in Appendix A. Students voted on the ideas they wanted to work on, resulting in a list of the top eight ideas. Then, the teaching team organized students into five teams according to student interest, skill, and team dynamics. For the rest of the five weeks, teams reiterated through their design by incorporating user interviews and feedback into their ideation process to refine their ideas.

Student Skill Development

Students initially developed their skills in manufacturing, electronics, entrepreneurship, and design through lessons and lectures, but once their project ideas were established, their learning was driven by the emerging demands of their team project. Members of the teaching team lead workshops for students to learn to use 3D CAD programs, such as by making a logo on top of a 1" by 1" by 0.25" base template or a desktop name tag using program functions, and then 3D printing it to take home. Students continued to practice rapid prototyping by making cardboard prototypes and 3D printing electronics housing, motor mounts, connectors for their projects and received help from a member of the teaching team to learn advanced techniques for the model they created. Some groups also learned to laser cut acrylic sheets for their project. Students were also given a tour of the machine shop but did not need to find the need to use the tools there to manufacture their projects. In the first two weeks, students also learned basics in electronic circuitry such as electrical symbols or diagrams and Ohm's law in a classroom setting. They also learned to write Arduino programs in classroom workshops, to operate a light emitting diode, motor, water level sensor, piezo buzzer, and liquid crystal display.

In weeks three and four, students experienced the iterative nature of the design process, by continually making improvements to their existing designs. At this point, teams had components working separately as proof of concepts. Students also learned more about mechanical and electrical design from the problems they encountered. For example, a student was guided to try an alternate power source when they asked a TA why their motor was spinning slowly. When a device that was built to flip a page did not work, students learned to experiment with different designs, occasionally asking for recommendations. One team had trouble getting a winch and pulley system to close a mechanical glove, so the instructor suggested to simplify the mechanism and reduce the number of parts such as the gears. Students also acquired feedback while exercising HCD with their classmates and end users through interviews and surveys. They exercised inquiry by learning to ask meaningful questions, allowing them to learn independently about topics they had limited knowledge on. Some examples of feedback students received were a request for a friendlier user interface for quality of life improvements. In response, one team added an electronic display in order for the device to "speak" to the user while another team added blinking lights to indicate the ready state of the device.

In weeks five and six, teams arrived at a minimum viable product that combined the majority of the features and components they had been building in the previous weeks. Students took video demonstrations of their working projects for the final presentation. They documented their progress in their presentations and created a website from sites online templates such as Wix, imitating a "launch page" for a general audience to read. In the final day of the program, teams pitched their final presentations to an audience consisting of student participants of other sections of the summer program, their parents, members of the community at Cooper Union, and other invited guests. Their demonstration videos and related CAD work were included in the presentation to convince the audience of the significance of the innovation they developed.

Survey Methods

Student Candidate Selection

The Summer STEM program considered sophomore and junior year high school applicants of varying socioeconomic, ethnic, and academic backgrounds. Advertisements for the Summer STEM program were distributed to high schools in the New York City metropolitan area. Candidates that applied were required to complete an essay on their interests and experience related to the program offering, provide a transcript and request a recommendation letter. Applicants were screened for a grade point average higher than 75 and a class record that indicated they were on track in their academic career, with qualities of leadership, collaboration, and creativity. Applicants without prior experience in a pre-college engineering program were given preference. Applicants from other college preparation programs in New York City were also given preference. The admitted student group was balanced to prevent overrepresentation of students from a single high school or program to reflect the demographics of New York City. Students typically had a grade point average of 87-93 out of 100. Scholarships were provided based on family income after the student was accepted.

Survey Logistics

An entry (presurvey) and exit (postsurvey) questionnaire pair for 2018 was designed to evaluate student development through the use of Likert scale, checkbox, and open-ended questions, approved by the Cooper Union Institutional Review Board. The questions and selectable responses to the presurvey are recorded in Appendix B, while those to the postsurvey are recorded in Appendix C. Participants were students in the summer STEM program, with student and parent consent for taking this voluntary survey. The teaching team encouraged students to participate in optional surveys to help improve the curriculum for future participants. Each student was assigned a random 4 digit code which matched their presurvey to postsurvey, but student identities remained anonymous. The presurvey was given at the beginning of the program and had 16 out of 19 students submit responses. The postsurvey was given at the end of the program and had 14 of the 18 students remaining submit the postsurvey. This Survey Methods section describes trends observed for selected survey questions. Survey participant demographics are recorded in Table 2.

Table 2. Survey Participant Demographics

	2018 Presurvey	2018 Postsurvey	2017 Survey
# of Questions	35	37	17
Students Enrolled at time of Survey	19	18	29
Student Responses	16	14	19
Response Rate	84%	78%	66%
Junior	44%	N/A	N/A
Senior	56%	N/A	N/A
Male Students	69%	N/A	67%
Female Students	31%	N/A	33%

The 2018 Makerspace section started with 19 students and concluded with 18 students because one student had to return home to a different state due to a family emergency. The 2017 Makerspace had a postsurvey with different questions and did not have a presurvey. The 2018 surveys addressed skills more specifically and included more questions relevant to the curriculum, so it was considered an improvement over the 2017 surveys. As a result, it was not possible to meaningfully compare most of the questions in the 2017 survey to that of the 2018 survey except for a few. The 2017 Makerspace cohort had a class size of 30 students in with a 1.5 male/female ratio with a 63% completion rate for an exit survey only. The 2018 Makerspace cohort had a class size of 18 students in with a 2.0 male/female ratio with an 83% completion rate for an entry survey and a 72% completion rate for an exit survey. Only the 2018 presurvey had the question "I think the group that is most like me is..." and yielded a distribution for student self-identification of ethnicity, depicted in Table 3. Students were allowed to pick one or more answers for this question so the sum of individual ratios does not add up to a total of 100%.

Table 3. Survey Participant response to "I think the group that is most like me is...)

Answer Choices	Responses
African American, Black	18.75%
American Indian, Native American, or Alaskan Native	0.00%
Asian, Asian-American	31.25%
Caribbean Islander	0.00%
Latino or Hispanic	18.75%
Middle Eastern or Arab	6.25%
Native Hawaiian, Pacific Islander	6.25%
White, Caucasian	37.50%
Prefer not to answer	12.50%
Other (please specify)	0.00%

In the 2017 Makerspace survey, the majority of questions were Likert Scales with a response of 1 representing "Strongly Disagree" and 5 representing "Strongly Agree" alongside open-ended responses. The questions student to do a self-assessment on their knowledge of what engineers do, their interest, and skills in engineering, and related work such as presentations and research.

In the 2018 Makerspace surveys, similar Likert scale questions were used, but new checkbox questions and new open-ended questions were added. The updated 2018 survey questions specifically addressed four specific fields of experience that characterized the makerspace curriculum into four skill categories: electronic, manufacturing, entrepreneurship, and design skills. The reason for this categorization was to specifically define student skill sets. Instead of previous survey questions that asked a Likert scale question to assess engineering knowledge such as "I know how to use basic electronic tools", the 2018 survey included both the Likert scale and checkboxes for specific skills or tools in order to better quantize and compare student knowledge before and after the program.

In the 2018 presurvey and postsurvey, 4-point Likert scale questions titled “Engineering Knowledge and Skills” listed various skills associated with engineering that allowed students to self evaluate their abilities before entering the program in the presurvey and re-evaluate at the end of the program in the postsurvey. Response choices included “Strongly Disagree”, “Disagree”, “Agree”, and “Strongly Agree”, with a numerical value of 1-4 respectively. Stacked bar charts were generated for the Results section of this paper to illustrate the number of responses in each degree.

The presurvey and postsurvey also included a 5-point Likert scale question titled, “I am confident in starting a new project that requires...” with the subsections “Electronic Skills”, “Manufacturing Skills”, “Entrepreneurship Skills”, and Design Skills”. Response choices included “Strongly Disagree”, “Disagree”, “Neither agree nor disagree”, “Agree”, and “Strongly Agree”, with a numerical value of 1-5 respectively. Stacked bar charts and double bar charts were generated to illustrate the number of responses in each degree.

Checkbox questions presented students with a list of skills in which they could select one or more skills they knew at the time of response. These four questions were “What ___ skills do you have experience in?” with the blank filled by one of four categories: “electronics”, “manufacturing”, “entrepreneurship”, and “design”. These questions had between 8 to 9 unique checkboxes as answers, where students could check one or more of the skills or tools listed, or the checkbox designating “none”. All four checkbox questions for “What ... skills do you have experience in?” were displayed as double bar charts.

Open-ended questions such as, “I would have liked to have been taught skills such as...” gave students an opportunity to provide feedback to help the instructor improve the curriculum for the following year. The analysis of these responses was not displayed in the paper, but can be found in Appendices B and C.

Graphical comparisons were created to compare the 2018 Makerspace entry presurvey and exist postsurvey results. Corresponding Likert Scale questions for the presurvey and postsurvey results were displayed as stacked bar charts for the “Engineering Knowledge and Skills” and “I am confident in starting a new project that requires…” questions.

Results

For the 2018 Makerspace class, presurvey and postsurvey responses were compared to identify areas where student self-reporting and perception of their abilities changed as a result of their participation in the program. Additional Likert questions such as “To what extent do you agree with the following statements?” were not included in the results section because most statements were more generic than the other questions. However, there was one particular Likert question that was not depicted in the following graphs. The average responses for the statement “I intend to pursue a science or engineering major in college” decreased from 4.38 to 4.21, and the average response to the statement “I am interested in working in a career that allows me to use Engineering related skills or knowledge” decreased from 4.44 to 4.14.

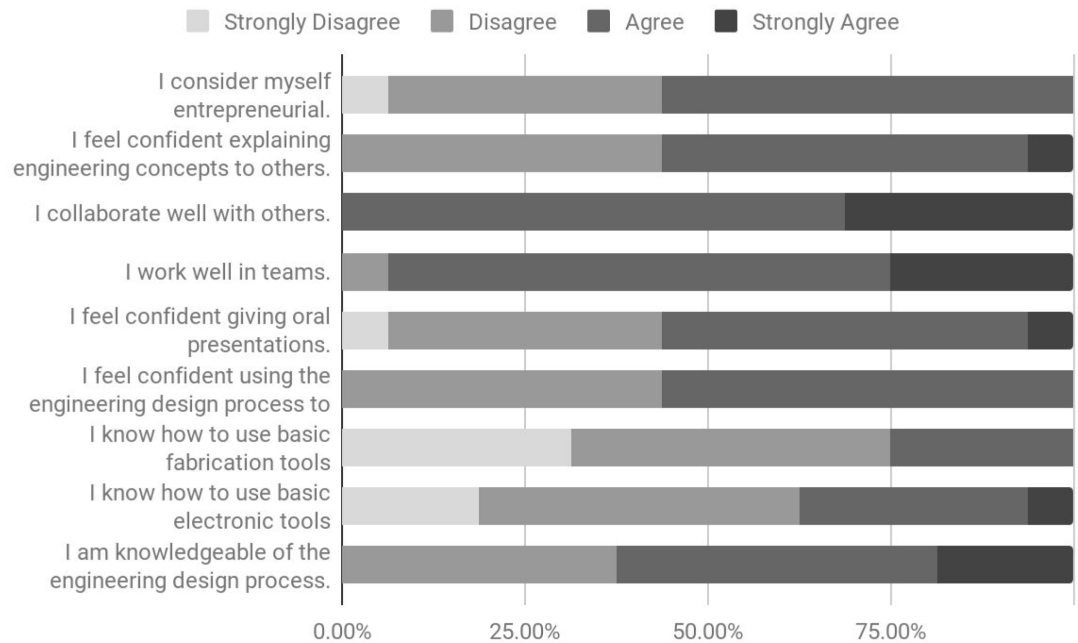

Figure 1. Engineering Knowledge and Skills (Presurvey)

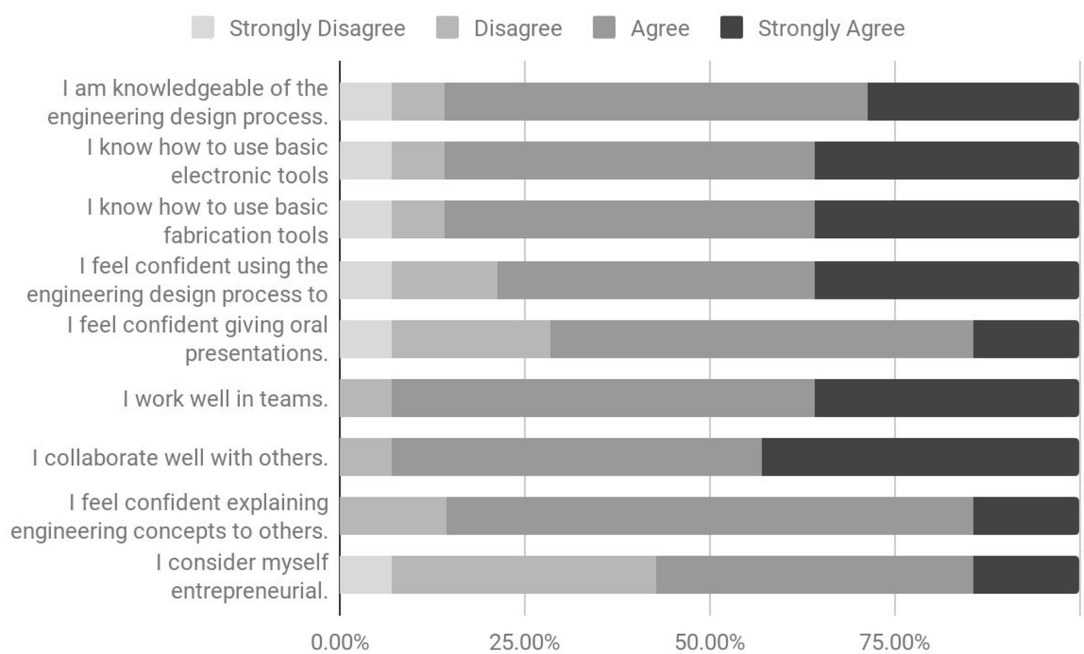

Figure 2. Engineering Knowledge and Skills (Postsurvey)

Between the presurvey and postsurvey results for “Engineering Knowledge and Skills” depicted in Figures 1 and 2, there was an increase in the number of “Strongly Agree” answers across all categories. There was a general decrease in the number of “Strongly Disagree” and “Disagree” responses in most categories.

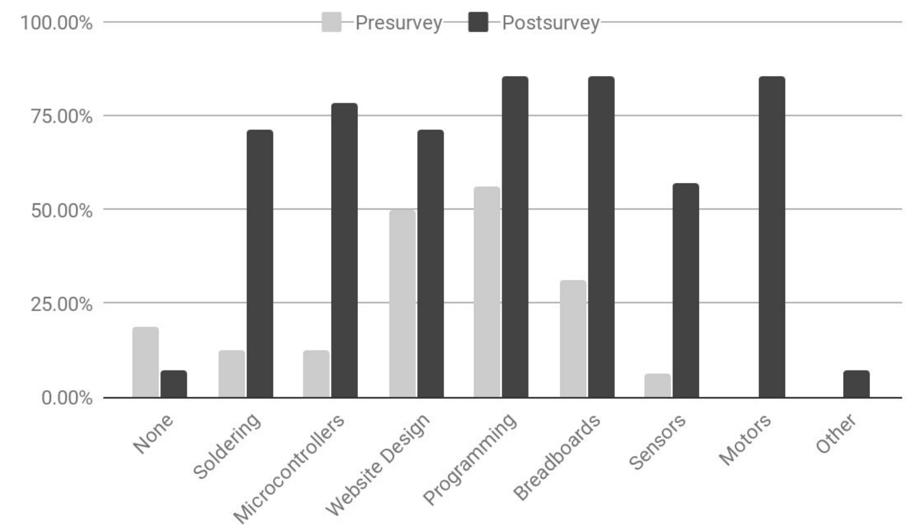

Figure 3. Responses to “What electronics skills do you have experience in?”

Between the presurvey and postsurvey responses in Figure 3, there was a decrease in the number of responses of “None”. Particular skills that had approximately than 50% increase in being checked for experience included soldering, microcontrollers, breadboards, sensors, and motors. About half of the survey participants entered with experience of website design and programming, and about three-quarters left with experience in website design.

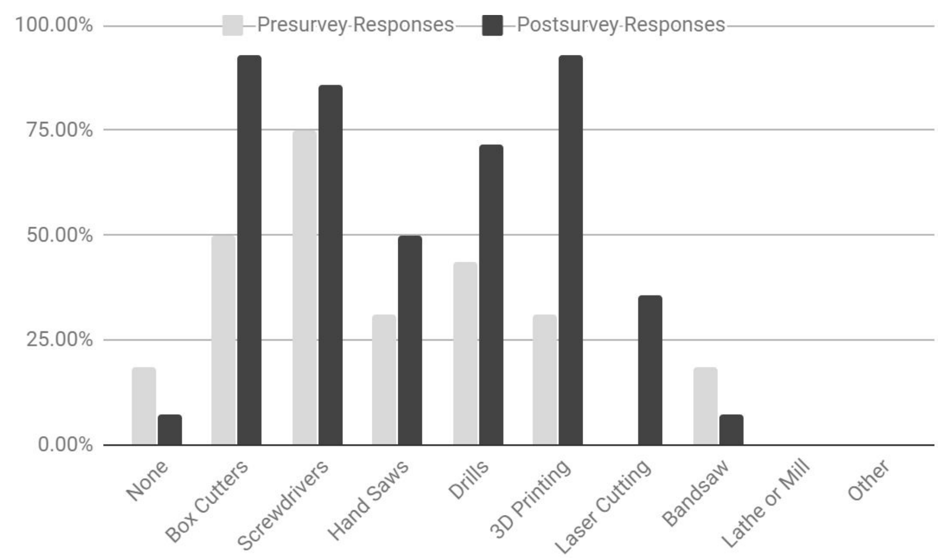

Figure 4. Responses to “What manufacturing skills do you have experience in?”

To questions about manufacturing skills, there was a decrease in the number of responses of “None” between the presurvey and the postsurvey (Figure 4). In the presurvey, 75% of student participants responded they had experience with screwdrivers, between 25-50% reported that they had experience with box cutters, hand saws, drills, and 3D printing. No students responded that they had experience with laser cutting and some students responded that they had experience with bandsaws. All of the mentioned skills had an increase, especially in box cutters and 3D printing with an increase of approximately 50%.

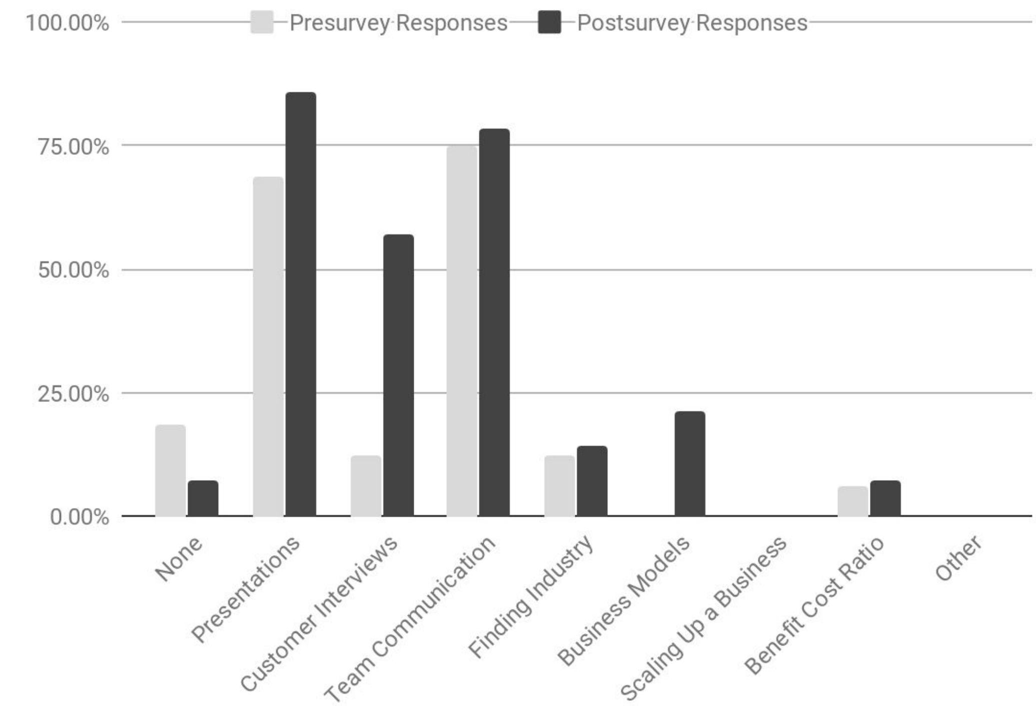

Figure 5. Responses to “What entrepreneurship skills do you have experience in?”

Between the presurvey and postsurvey responses in Figure 5, there was a decrease in the number of responses of “None”. In the presurvey, almost 75% of student participants responded they had experience with presentations and team communication, which increased slightly in the postsurvey. Students response for customer interviews increased by approximately 50%, while the response for business models increased by almost 25%. The responses for finding industry leaders, scaling up a business, and benefit-cost ratio remained approximately the same.

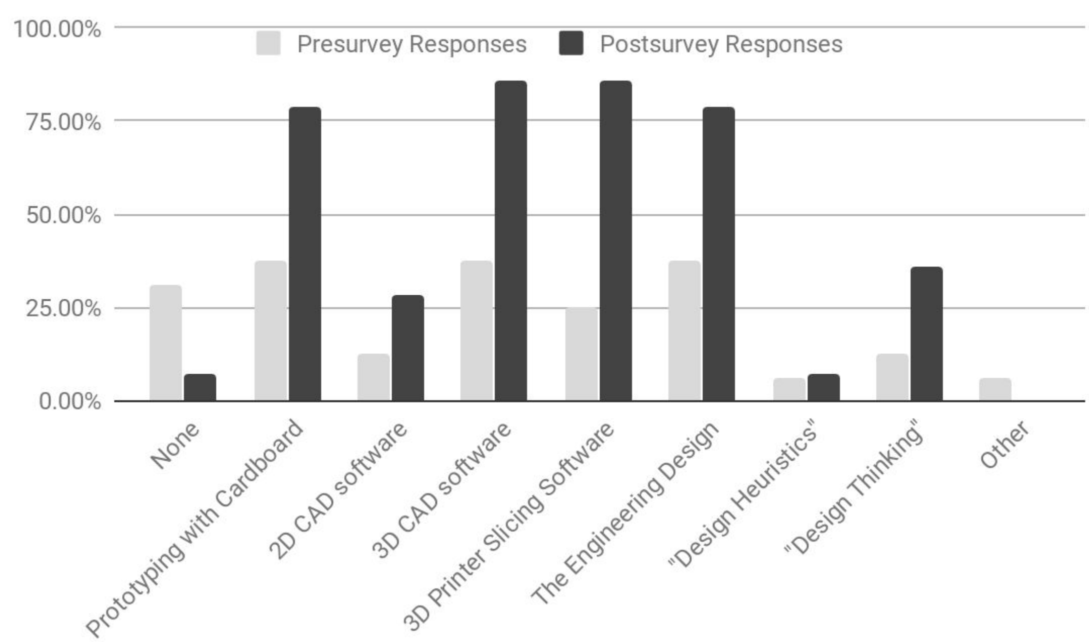

Figure 6. Responses to “What design skills do you have experience in?”

Between the presurvey and postsurvey responses in Figure 6, there was a decrease in the number of responses of “None” by approximately 25%. Students responses for prototyping with cardboard and tape, 3D CAD software, and the Engineering Design Process approximately doubled with an increase of about 50%. The response for 2D CAD software and Design Thinking increased slightly and response Design Heuristics remained approximately the same.

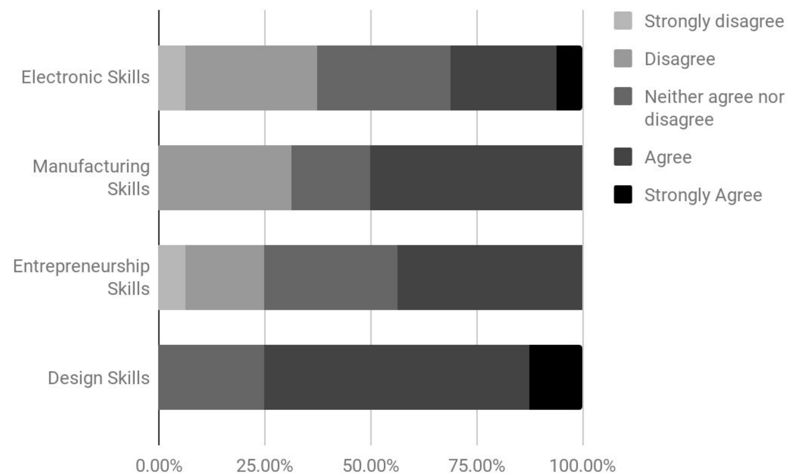

Figure 7. Responses to “I am confident in starting a new project that requires…” (Presurvey)

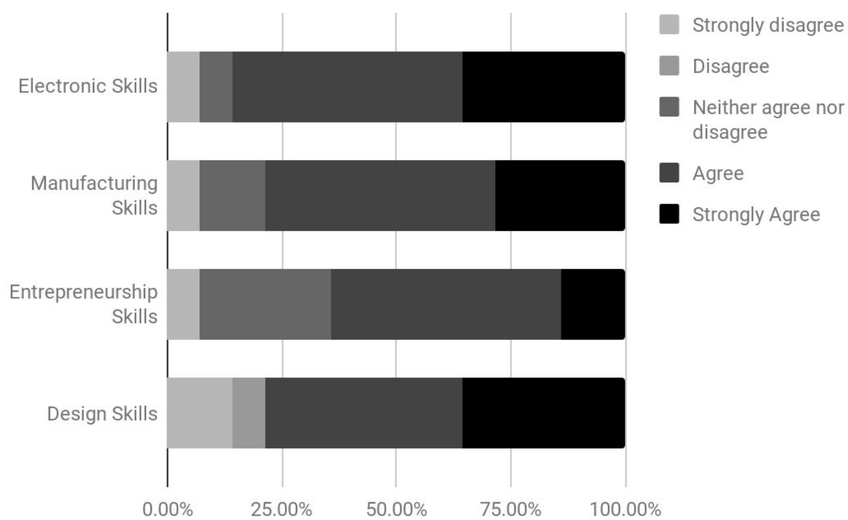

Figure 8. Responses to “I am confident in starting a new project that requires…” (Postsurvey)

Students responses to “I am confident in starting a new project that requires…” showed an increase in the number of “Strongly Agree” answers across all categories between the presurvey and the postsurvey (Figures 7 and 8). There was also an increase in the number of “Strongly Agree” answers across every category. However, there was also a 15% increase in “Strongly Disagree” answers for Design Skills. There was a decrease in the number of “Neither agree nor disagree” and “Disagree” responses in all categories, but an equal or higher number of “Strongly Disagree” responses in all categories.

Discussion

Introductory lessons and weekly practice likely contributed to the overall increase in average Likert Value responses for presentations, teamwork, and application of manufacturing, electronics, entrepreneurship, and design skills (Figure 1). Compared to the presurvey, more students in the postsurvey indicated that they had the engineering skills listed and agreed that they were skilled in the four categories of “electronics”, “manufacturing”, “entrepreneurship”, and “design” shown in Figures 2-5. Students probably indicated they did not know everything in the checkbox questions since team responsibilities were divided so members could specialize and master particular skills for greater team efficiency. For example, a student who focused on programming radio frequency pairs may not have considered themselves to have a strong understanding of motors. The decrease in the number of students who checked “bandsaw” in Figure 4 might be explained as mistaken assumptions on identifying a bandsaw at the start of the program, but later correctly recognizing it without having used it. In the same figure, an unchanged response rate of zero for mills and lathes indicated students did not have experience in using them and did not need to use them in manufacturing parts, despite their availability in the machine shops.

In Figure 5, the responses for finding industry leaders, scaling up a business, and benefit-cost ratio remained approximately zero, due to the lack of instruction on these categories during the curriculum, despite the intent to do so when the survey was created. In Figure 6, the small increase in experience with 2D CAD can be attributed to how only students in certain groups that needed to use laser cutting acquired the skill in the case-by-case basis. The teaching team expected a higher response rate for student knowledge of “Design Thinking” since it was taught and there was an increase in responses to “Customer Interviews” in Figure 5. The unmet expectation might be because students were not taught to associate the phrase “Design Thinking” to user interviews even if they were using it. Design Heuristics was left out of the curriculum which resulted in no change in responses for that category. Between Figures 7 and 8, the average Likert value to the statement “I am confident in starting a new project that requires: Electronic Skills, Manufacturing Skills, Entrepreneurship Skills, and Design Skills” are depicted in Table 4.

Table 4. Student confidence in skills to start a new project (pre- and post- surveys)

	Electronic Skills (1-5)	Manufacturing Skills (1-5)	Entrepreneurship Skills (1-5)	Design Skills (1-5)
2018 Presurvey	2.63	2.69	2.69	3.13
2018 Postsurvey	3.20	3.21	3.00	3.00

There was a decrease in the average value of confidence in starting projects using design skills. This was unexpected due to the increase of individual responses of “Strongly Agree” and “Agree” across all four categories, and a decrease in responses of “Neither agree nor disagree” and “Disagree” across starting a project. However, the increase in responses where students “Strongly Disagree” with their confidence in design work, can be interpreted a student’s new uncertainty to start a design project due to the challenges or complications they faced.

There was an overall decrease in average Likert scale response values, depicting a decrease in interest to continue pursuing engineering. The Likert value response for the statement “I intend to pursue a science or engineering major in college” decreased from 4.38 to 4.21, and the average response to “I am interested in working in a career that allows me to use Engineering-related skills or knowledge decreased from 4.44 to 4.14. This suggested that participants were less interested in engineering majors and careers despite having been exposed to samples of engineering skills, activities, and curriculum. Due to the small participant size of fewer than 20 students in the classroom, the trends discovered in this study may not be statistically significant.

Conclusions and Recommendations

The introduction of HCD into the 2018 Makerspace curriculum reinforced student independence in their learning processes, and also improved the Project-Based Learning experience for students. The teaching team identified that the final designs at the end of 2018 Makerspace had problem statements that were better defined and used technology more practically compared to those in previous years. The additional emphasis of Inquiry-Based Learning in HCD helped students think independently to ask significant questions that motivated their investigation of a meaningful problem statement and solution. The additional emphasis of Problem-Based Learning grounded students to identify real-world problems and create a solution rather than make a project that only solved a hypothetical problem.

In previous years, the teaching team was more active in the student decision-making process and encouraged students to improve their skills, but also resulted in increasingly complicated and impractical solutions, like with traditional testing based culture. For example, student projects in 2017 featured connections as part of their innovative solutions but required advanced programming skills which required TAs to extensively write and debug the code for students. This is compared to 2018, where one student team used HCD to recognize the cost and complexity behind Bluetooth and ended up using radio frequency instead which was also easier to learn and program.

Student teams in 2018 produced innovations that were more practical to prototype in six weeks, had better user feedback and overcame reasonable challenges because they grounded their design process with real-world applications in HCD and the product market fit. Based on survey results, the improvement in the achievability of design milestones most likely reinforced student self-efficacy. Trends revealed that students generally felt more confident in their self-assessment of their electrical, manufacturing, entrepreneurship, and design skills after completing the Makerspace section. This may be due to the application of HCD to combine inquiry and problem when asking questions to identify problems and solutions. The Engineering Design Process was placed into this framework, producing a Project-Based Learning experience that combined various pedagogies to help students take ownership of identifying, creating, iterating, and showcasing their inventions. However, another trend depicted a decrease in student interest in engineering, which could have been affected by student self-assessments if they believed that engineering is not they expected, based on their summer STEM experience at Cooper Union.

Future directions include refining the curriculum and teaching methods to yield the best experience for individuals and maximize student growth and engagement. Since individual students primarily learn through mentorship in skills and technologies when required by the project, it is important to consider accommodations according to the team project, team role, individual interests and aptitudes, and team dynamics. Lastly, a greater understanding of student college and career paths after participating in the Makerspace program can be achieved by developing a post-program survey. This addition of student tracking would provide a better scope to understand the lasting impact of Makerspace teaching methods on student education pathways.

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Appendix A: Student Individual Pitch Ideas

Name of your product/idea	**Briefly describe your product/idea (One line)**
Waterpik 2.0	My idea was to design a heater and a heat exchanger so that it will prevent inconsistent temperature and choosing the right temperature for people while taking a shower.
Anti-Procrastinator	It encourages the user to finish their work
Bright Bookmark	Bookmark with light
Brush Saver	Cleans paint brush with rotating DC motor
Blanket Coverage	Blanket for hospital patient that extends/retracts based on temperature
CoolCane	Attachment to a cane that allows it to stand upright and grab onto items
Robo-TrashCan	A trash can that moves around in the house
FIND	A GPS tracker with Bluetooth and SMS functionality to help you find lost/stolen items.
Convertible Game	Multiple games in one
“Watch” Your Kid	A watch that buzzes on the parent watch when the child has stepped over the perimeters, and the watch has a feature like a walkie talkie to communicate.
Stick-On Pocket	A stick-on pocket
Nap Saver	Helps the user from missing their subway stop because they are sleeping
Find-Fetch	Ability for items to be equipped with RFID chips and lights to find them faster and a conveyor belt system to bring a selected object to the user.
Grip Glove	A mechanism to increase astronaut hand mobility and reduce strain using an affordable design.
Garbage Dropper	This product holds garbage and drops it into a larger container outside.
SmartWallet	Bluetooth connected wallet that signals to phone when out of range so that people don't lose them.
The Running Belt	A light-weight, adjustable belt that can hold accessories and water so that people can run with all the items that they need.
Mechanical Page Turner	A device that automatically turns pages for musicians, people w/ disabilities
Combined Game	A combined game

Appendix B: Summer STEM 2018 Makerspace Student Presurvey

Q1. Student ID#:

Q2. What grade are you entering in fall
Junior
Senior
other

Q3. Home Zip Code

Q4. How do you feel about engineering?
I get excited about engineering.
I like to participate in engineering projects.
I want to understand engineering.
I like to see how things are made.
I get excited to learn about new discoveries.
I pay attention when people talk about the environment.
I am curious to learn more about cars that run on electricity.
I am interested in engineering inventions.
I would like to have an engineering job in the future.
I enjoy playing games that teach me about engineering.
I like to make things.
I enjoy learning new ideas about engineering.
I have fun reading and learning about engineering.
I enjoy doing engineering problems.
Working hard now will help me do engineering work later.

Q5. Engineering Knowledge and Skills
I am knowledgeable of the engineering design process.
I know how to use basic electronic tools (Examples: Oscilloscope, power supplies, breadboard, circuit components, etc)
I know how to use basic fabrication tools (Examples: Laser cutter, 3D printer, machine shop, etc)
I feel confident using the engineering design process to solve a problem.
I feel confident giving oral presentations.
I work well in teams.
I collaborate well with others.
I feel confident explaining engineering concepts to others.
I consider myself entrepreneurial.

Q6. What electronics skills do you have experience in?
None
Soldering
Microcontrollers
Website Design
Programming
Breadboards
Sensors
Motors
Other (please specify)

Q7. What manufacturing skills do you have experience in?
None

Box Cutters or Hobby Knives
Screwdrivers
Hand Saws
Drills
3D Printing
Laser Cutting
Bandsaw
Lathe or Mill
Other (please specify)

Q8. What entrepreneurship skills do you have experience in?
None
Presentations
Customer/User Interviews
Team Communication
Finding Industry Experts or Mentors
Business Models
Scaling Up a Business
Benefit Cost Ratio
Other (please specify)

Q9. What design skills do you have experience in?
None
Prototyping with Cardboard or Household Materials
2D CAD software (i.e. AutoCAD)
3D CAD software (i.e. Solidworks, Inventor, Rhino)
3D Printer Slicing Software (i.e. Tinkerine Suite, Cura, Slic3r)
The Engineering Design Process
"Design Heuristics"
"Design Thinking"
Other (please specify)

Q10. I am confident in starting a new project that requires
Electronic Skills
Manufacturing Skills
Entrepreneurship Skills
Design Skills

Q11. Why are/aren't confident in starting a new project that requires ELECTRONICS skills?

Q12. Why are/aren't confident in starting a new project that requires MANUFACTURING skills?

Q13. Why are/aren't confident in starting a new project that requires ENTREPRENEURSHIP skills?

Q14. Why are/aren't confident in starting a new project that requires DESIGN skills?

Q15. College Awareness
Understanding admission requirements for colleges I am interesting in attending.
Finding information on college life.
Completing a college application form.
Completing a financial aid form (FAFSA).
Writing an application essay.
Knowing what services are available at colleges that can help me succeed.
Using strategies to advocate for myself.

Q16. Do you plan to enroll in an educational program the year after high school graduation?
Yes – a 2 year Community / Vocational or Technical School
Yes – a 4 year college
Yes – through military enlistment
Yes – not sure yet
No – not planning to attend school the year after high school graduation

Q17. What is the highest level of education you plan to complete beyond high school?
Specialized training or certificate program
Two year associate of arts or science degree (AA, AAS, or AS)
Bachelor's degree (BA or BS)
Graduate degree (MA, MBA, MS, PhD, JD, MD, or DVM)
Undecided
Other (Please describe)

Q18. To what extent do you agree with the following statements?
I intend to pursue a science or engineering internship or research rotations between now and college.
I intend to pursue a science or engineering major in college.
I am interested in taking ENGINEERING courses in college.
I am interested in working in a career that allows me to use ENGINEERING-related skills or knowledge.

Q19. Career Awareness
I know about different kinds of engineering jobs.
I know where to find information about engineering jobs.
I know of companies that hire people to work in engineering jobs.

Q20. What are your perceptions of what engineers do?
Engineers do many different kinds of work.
Engineers are creative people.
Anyone who wants to can become an engineer.
Engineers make a lot of money.
Engineers do boring things.
Engineers need to be good problem-solvers.
Engineers always agree on the best way to solve a problem.
Engineers use lots of ways to communicate ideas.
Engineers need to be good at math.
Engineers do a lot of work with their hands.
Engineers do a lot of work with their brains.
Engineers get to be the boss.
Engineers discover new knowledge.
Engineers design new things.
Engineers usually work alone.

Q21. Is what you learn in engineering important?
Engineering is important to me.
Engineering is important for what I want to study later.
Engineering will help me find a job.

Q22. Please indicate which of the math courses listed below you have taken.
Algebra I
Geometry
Algebra II/ Trigonometry
Pre-Calculus

Calculus
Differential Equations
Other (please specify)

Q23. Please indicate which of the science or engineering courses listed below you have taken.
Living Environments
Earth Science
Basic Chemistry
Organic Chemistry
Biology
Physics - Mechanics
Physics - Electricity and Magnetism
AP or Honors Chemistry
Introduction to Engineering
Computer Science: Basic programming
Computer Science: Advanced programming
AP Computer Science A
AP Computer Science Principles
Statistics
Other (please specify)

Q24. Please indicate which of the computer programming languages listed below you have used.
C/C++
Java
HTML
Python
Scratch
Ruby
Other (please specify)

Q25. Have you had any previous experiences either internship, volunteer work, or independent project in science and/or engineering research?
No experience
At college other than Cooper Union
At a company
At a museum or cultural organization
At a hospital or health care center
Class or after school project at my own high school
Class or after school project at another high school
Other (please specify)

Q26. Did you apply to any other Summer program(s) for STEM?
No
Yes

Q27. If you answered yes above, please list here:

Q28. Were you accepted into any of these Summer program(s)?
No
Yes
Did not apply

Q29. If you answered yes above, what program was it?

Q30. How did you learn about this program?
Teacher
Principal
Student
Brochure
Internet
Other (please describe)

Q31. Why did you choose the Summer STEM program at Cooper Union?

Q32. What is your gender?
Male
Female
Other
Prefer not to answer

Q33. I think the group that is most like me is: (Please pick one or more of the groups below)
African American, Black
American Indian, Native American, or Alaskan Native
Asian, Asian-American
Caribbean Islander
Latino or Hispanic
Middle Eastern or Arab
Native Hawaiian, Pacific Islander
White, Caucasian
Prefer not to answer
Other (please specify)

Q34. I speak a language OTHER than English at home:

Appendix C: Summer STEM 2018 Makerspace Student Postsurvey

Q1. Student ID#:

Q2. What grade are you entering in fall
Junior
Senior
other

Q3. Home Zip Code

Q4. How do you feel about engineering?
I get excited about engineering.
I like to participate in engineering projects.
I want to understand engineering.
I like to see how things are made.
I get excited to learn about new discoveries.
I pay attention when people talk about the environment.
I am curious to learn more about cars that run on electricity.
I am interested in engineering inventions.
I would like to have an engineering job in the future.
I enjoy playing games that teach me about engineering.
I like to make things.
I enjoy learning new ideas about engineering.
I have fun reading and learning about engineering.
I enjoy doing engineering problems.
Working hard now will help me do engineering work later.

Q5. Engineering Knowledge and Skills
I am knowledgeable of the engineering design process.
I know how to use basic electronic tools (Examples: Oscilloscope, power supplies, breadboard, circuit components, etc)
I know how to use basic fabrication tools (Examples: Laser cutter, 3D printer, machine shop, etc)
I feel confident using the engineering design process to solve a problem.
I feel confident giving oral presentations.
I work well in teams.
I collaborate well with others.
I feel confident explaining engineering concepts to others.
I consider myself entrepreneurial.

Q6. What electronics skills do you have experience in?
None
Soldering
Microcontrollers
Website Design
Programming
Breadboards
Sensors
Motors
Other (please specify)

Q7. What manufacturing skills do you have experience in?
None

Box Cutters or Hobby Knives
Screwdrivers
Hand Saws
Drills
3D Printing
Laser Cutting
Bandsaw
Lathe or Mill
Other (please specify)

Q8. What entrepreneurship skills do you have experience in?
None
Presentations
Customer/User Interviews
Team Communication
Finding Industry Experts or Mentors
Business Models
Scaling Up a Business
Benefit Cost Ratio
Other (please specify)

Q9. What design skills do you have experience in?
None
Prototyping with Cardboard or Household Materials
2D CAD software (i.e. AutoCAD)
3D CAD software (i.e. Solidworks, Inventor, Rhino)
3D Printer Slicing Software (i.e. Tinkerine Suite, Cura, Slic3r)
The Engineering Design Process
"Design Heuristics"
"Design Thinking"
Other (please specify)

Q10. The design methods I learned...
Have helped me develop effective design alternatives
Have helped me develop designs that people actually want
Are practical for me to continue using on my own

Q11. Outside of class each week, I spent this many hours on average doing research related to my project.

Q12. Outside of class each week, I spent this many hours on average improving the design of my project.

Q13. At the end of the program, I thought of this many design alternatives for the project(s) I worked on in Makerspace.

Q14. I was taught PROGRAMMING skills that I don't find useful, such as:

Q15. I was taught ELECTRONICS skills that I don't find useful, such as:

Q16. I was taught MANUFACTURING skills that I don't find useful, such as:

Q17. I was taught ENTREPRENEURSHIP skills that I don't find useful, such as:

Q18. I was taught DESIGN skills that I don't find useful, such as:

Q19. I would have liked to have been taught PROGRAMMING skills such as:

Q20. I would have liked to have been taught ELECTRONICS skills such as:

Q21. I would have liked to have been taught MANUFACTURING skills such as:

Q22. I would have liked to have been taught ENTREPRENEURSHIP skills such as:

Q23. I would have liked to have been taught DESIGN skills such as:

Q24. I am confident in starting a new project that requires
Electronic Skills
Manufacturing Skills
Entrepreneurship Skills
Design Skills

Q25. Why are/aren't confident in starting a new project that requires ELECTRONICS skills?

Q26. Why are/aren't confident in starting a new project that requires MANUFACTURING skills?

Q27. Why are/aren't confident in starting a new project that requires ENTREPRENEURSHIP skills?

Q28. Why are/aren't confident in starting a new project that requires DESIGN skills?

Q29. College Awareness
Understanding admission requirements for colleges I am interesting in attending.
Finding information on college life.
Completing a college application form.
Completing a financial aid form (FAFSA).
Writing an application essay.
Knowing what services are available at colleges that can help me succeed.
Using strategies to advocate for myself.

Q30. Do you plan to enroll in an educational program the year after high school graduation?
Yes – a 2 year Community / Vocational or Technical School
Yes – a 4 year college
Yes – through military enlistment
Yes – not sure yet
No – not planning to attend school the year after high school graduation

Q31. What is the highest level of education you plan to complete beyond high school?
Specialized training or certificate program
Two year associate of arts or science degree (AA, AAS, or AS)
Bachelor's degree (BA or BS)
Graduate degree (MA, MBA, MS, PhD, JD, MD, or DVM)
Undecided
Other (Please describe)

Q32. To what extent do you agree with the following statements?
I intend to pursue a science or engineering internship or research rotations between now and college.
I intend to pursue a science or engineering major in college.
I am interested in taking ENGINEERING courses in college.
I am interested in working in a career that allows me to use ENGINEERING-related skills or knowledge.

Q33. Career Awareness
I know about different kinds of engineering jobs.
I know where to find information about engineering jobs.
I know of companies that hire people to work in engineering jobs.

Q34. What are your perceptions of what engineers do?
Engineers do many different kinds of work.
Engineers are creative people.
Anyone who wants to can become an engineer.
Engineers make a lot of money.
Engineers do boring things.
Engineers need to be good problem-solvers.
Engineers always agree on the best way to solve a problem.
Engineers use lots of ways to communicate ideas.
Engineers need to be good at math.
Engineers do a lot of work with their hands.
Engineers do a lot of work with their brains.
Engineers get to be the boss.
Engineers discover new knowledge.
Engineers design new things.
Engineers usually work alone.

Q35. Is what you learn in engineering important?
Engineering is important to me.
Engineering is important for what I want to study later.
Engineering will help me find a job.

Q36. Please indicate which of the computer programming languages listed below you have used.
C/C++
Java
HTML
Python
Scratch
Ruby
Other (please specify)

Q37. Is there anything else you would like to tell us about your Summer STEM experience?
Yes
No

Q35. If you answered yes above, what language other that English do you speak at home?