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Combining a Virtual Tool and Physical Kit for Teaching Sensors and Actuators to First-year Multidisciplinary Engineering Students

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Background & Motivation

Engineering Design and Society is a first-year makerspace-based course for all engineering students at the University of Florida to have hands-on experience with prototyping early in the curriculum. The technical skills covered as part of the course include individual student knowledge of hand tools, solid modeling, 3D printing, and Arduino-based microelectronics for control of engineering sensors and actuators. The course is focused on human-centered design and how engineers can use their design skills to help humanity. The overall structure of the course begins with two weeks on human-centered design, then five weeks on technical skills (solid modeling, 3D printing, Arduino electronics, introductory programming), and the last six weeks students work in multidisciplinary teams to design and build functional prototypes of a product to help society. At the end of the semester, teams create formal engineering design reports and give presentations of their functional prototypes.

This work focuses on one of the technical skills aspects of the course, the Arduino-based sensor and actuator kits and related curriculum. Each student in the course purchases an Arduino starter set as the course "textbook" for individual ownership and more personalized experimentation in learning about common engineering sensors and actuators. In parallel to the physical Arduino kits, the course recently introduced the use of Tinkercad Circuits as a virtual tool to deliver modules relating to beginning sensors and actuators knowledge, microcontroller inputs and outputs, and beginning block programming for control of Arduino-based sensors and actuators. The virtual Arduino tool and the physical student-owned kits are used in combination to introduce the importance of sensors and actuators across all engineering majors. Curriculum focuses on using the virtual simulation tool to build and test wiring and programming online before physically building the Arduino electronics. This virtual tool and physical kit combination allows students to separate any errors that may occur in their programming and paths in the virtual tool from any issues that may occur from their physical kit builds (loose wiring, bad sensors or actuator components, etc.) For the semester of this research study, Engineering Design & Society, a hands-on makerspace course, was switched to a fully online course due to COVID. In this temporality online form the course modality was structured as an online synchronous course with individual at-home Arduino laboratory kits plus the parallel Tinkercad Circuits virtual tool.

Researchers have investigated comparisons between student performance using either virtual or physical laboratories [1] [2]. Some studies have also investigated virtual tools that are a compliment to the physical laboratory activities [3]. In this course and research study the goal was to investigate a more cohesive utilization of both the virtual tool and physical kit for increased student understanding and ease of use of the physical Arduino kit through the Tinkercad Circuits virtual tool features. Research has shown this more blended use of virtual and physical tools in design yielded better educational results than either modality alone [4]. Specifically within electronics, the use of the combination of both the simulation and physical labs in conjuction with each other resulted in better student understanding of electronics concepts [5].

The learning objectives of the electronics portion of the first-year course include individual student confidence in selection, wiring, and programming of components to empower students to create functional “electronic guts” of their own engineering prototypes that take in signals from the environment and send controlled commands to actuators. This paper focuses on the integration of the Tinkercad Circuits Virtual tool for teaching block programming, control of sensors & actuators, and electronic prototyping. Impact on students is examined both qualitatively and quantitatively through student surveys on self-confidence in their Arduino-based use of sensors and actuators and introductory programming skills from course participation.

Tinkercad Circuits Tool & Course Use

The Tinkercad Circuits tool is a free online virtual tool for wiring, programming, and running virtual simulations of the function of Arduino-based sensors and actuators. It was chosen as an addition to the Engineering Design & Society course as a method to enhance the physical Arduino Starter Basic Kit each student purchases as a course “textbook”. This allows for individual virtual learning with the Tinkercad Circuits tool to parallel and support the individual hands-on electronics learning with the physical Arduino kits. Tinkercad Circuits recreation of Arduino components commonly utilized in prototyping is shown in Figure 1.

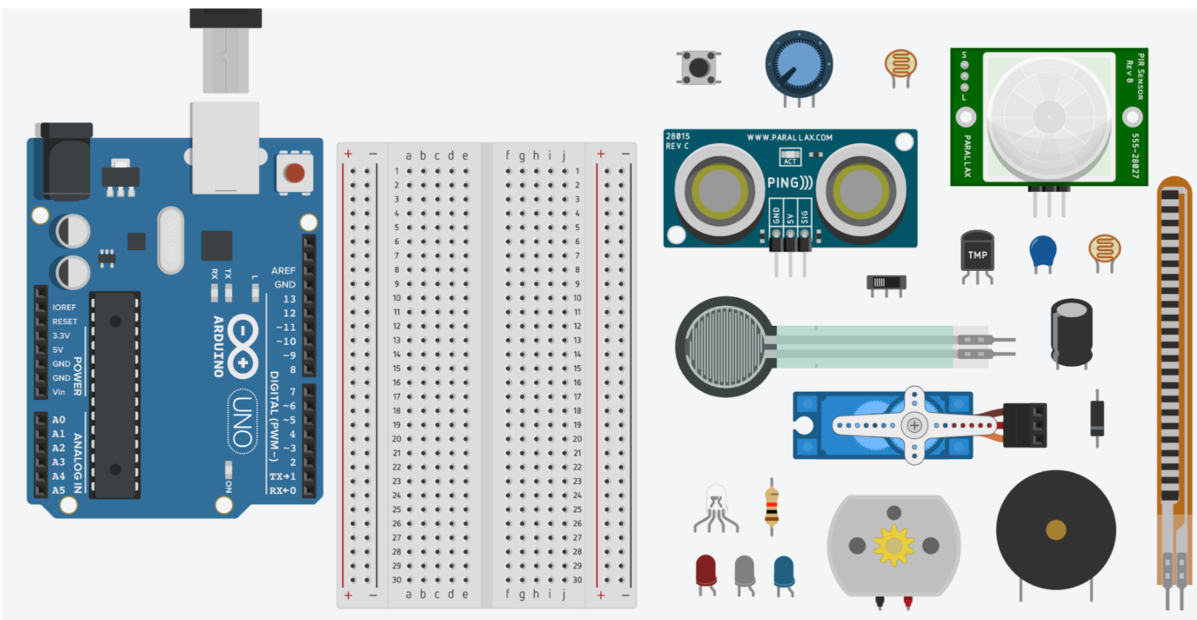

Figure 1: Arduino UNO microcontroller, breadboard, and variety of sensors and actuators commonly used in student prototyping available in the Tinkercad Circuits virtual tool.

One of the main components in consideration of adding Tinkercad Circuits to the curriculum was utilizing the block coding aspect of the software platform to introduce enough functional programming that first-year students could control engineering sensors and actuators without needing any previous programming experience. The Tinkercad Circuits interface has a well-structured beginning block coding with pull-in interlocking blocks for common introductory programming elements (Control, Math, Variables, Input, Output, and Notation). The code blocks are color-coded for function and geometrically constrained to only fit logically in the sequence they would be used in constructing a functional program. Figure 2 shows the collection of programming block elements available within the Tinkercad Circuits virtual tool for Arduino-based controls simulations.

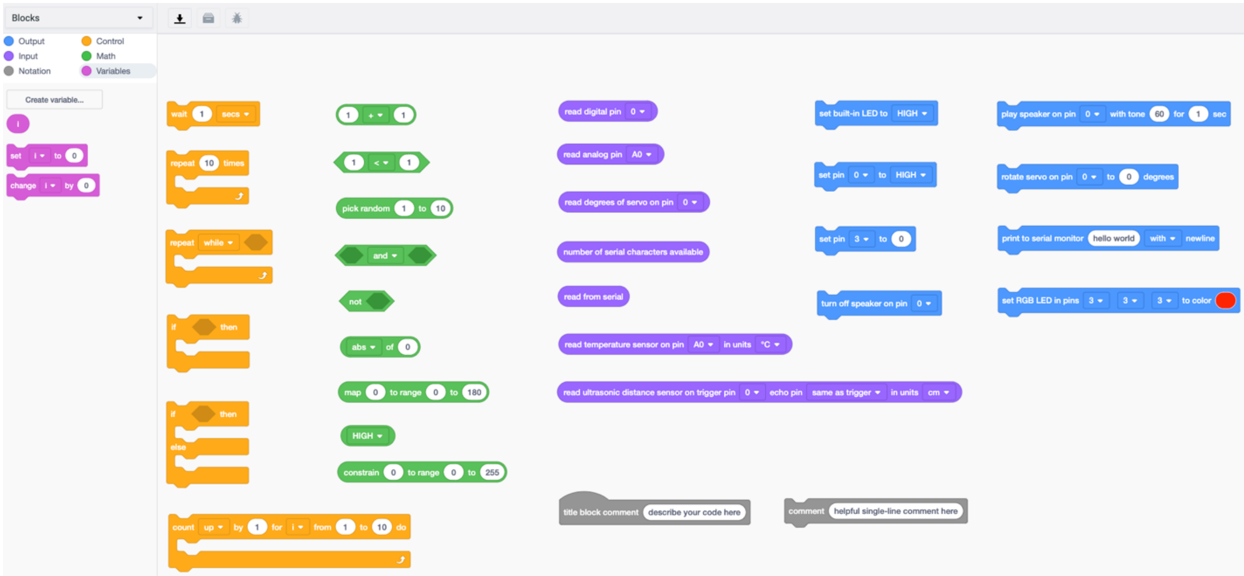

Figure 2: Programming block components available within Tinkercad Circuits Virtual Tool.

Within Tinkercad Circuits the virtual Arduino components and block coding are used in coordination to teach programming structure and Arduino microcontroller wiring channels for control of sensors & actuators. A series of on-demand instructional modules were created to introduce students to the Tinkercad Circuits environment and with build-along and code-along activities to enhance student understanding of the logic behind the block programming and wiring of the Arduino electronics. In addition to the on-demand modules students were given synchronous instruction in both wiring and block coding of components as part of two weeks of electronics content within Engineering Design & Society. Figure 3 shows the virtual tool interface with the coordination of wiring of Arduino components and control of those sensors & actuators through block coding.

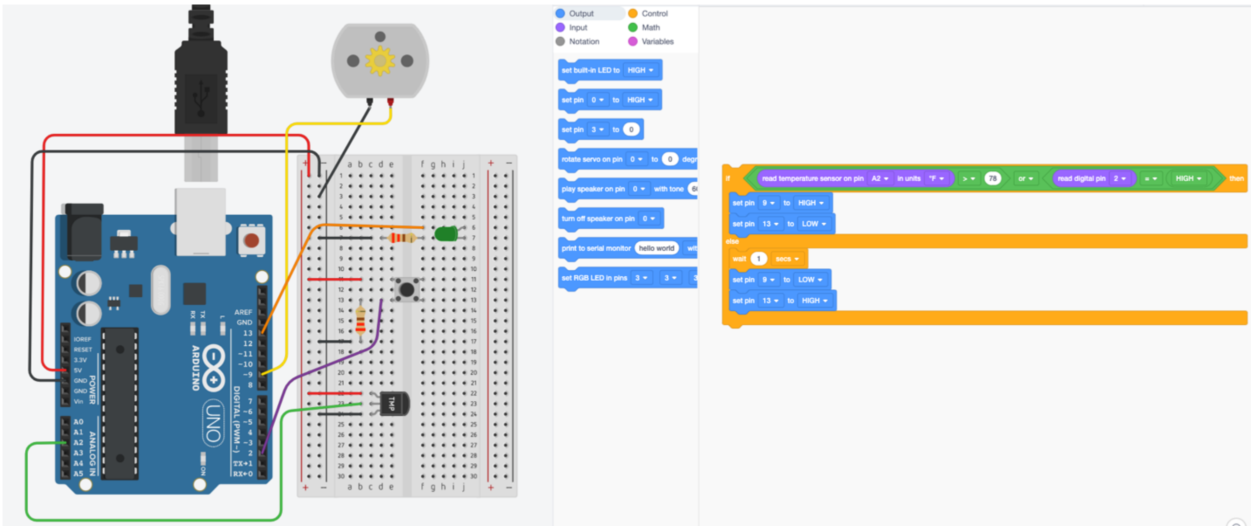

Figure 3: A sample Tinkercad Circuits build used in live instruction shown fully wired with accompanying block coding for interaction and control of sensors and actuators.

For Engineering Design & Society one of the main software uses is for students to virtually test and adjust the code or wiring of their electronics virtually with the Tinkercad Circuits tool before they physically build them with their Arduino Kits. The Tinkercad Circuits tools has live simulation mode, where the sensors can be activated by the user while the code is running to see if the actuators do the expected controlled response based on user code. Figure 4 shows a proximity sensor that lights up a certain number of LEDs based on how far away the user is. In simulation mode the user can actuate their mouse to activate the proximity sensor, and if wired and programmed correctly, the appropriate number of LEDs light up.

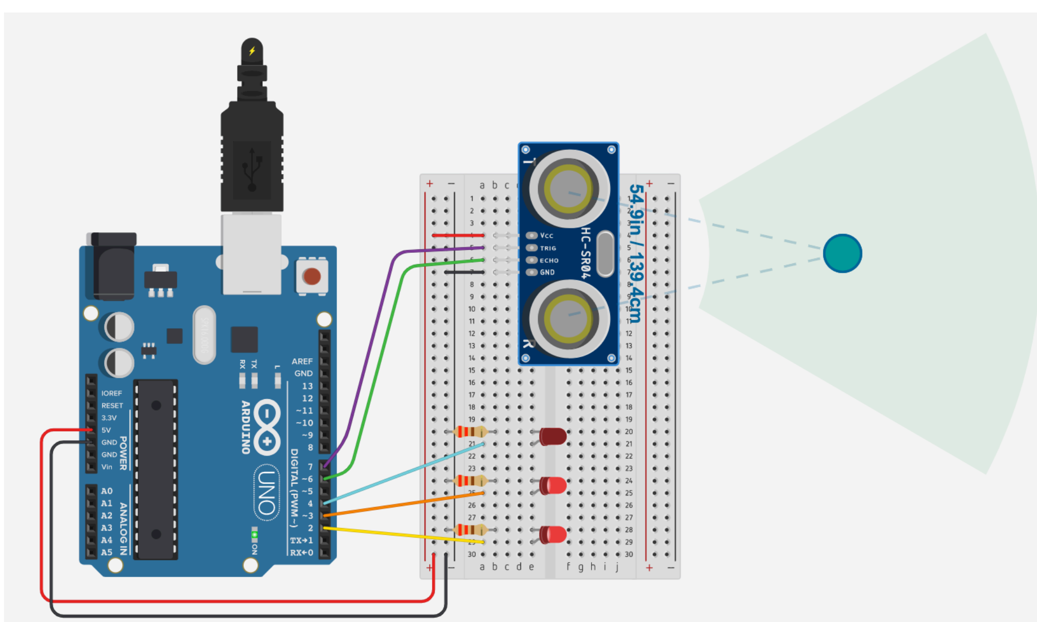

Figure 4: Demonstration of the virtual tool in simulation mode, where users can actuate sensors to see if programmed response of actuators coordinates to intended code logic.

Representative Student Work

Students are challenged in an assignment the week of programming instruction to individually create and program a functional Arduino-based design in Tinkercad circuits. Figures 5 (build) and Figure 6 (block code) are a typical sample of student work on this one-week individual skills assignment from a student who chose to use block programming.

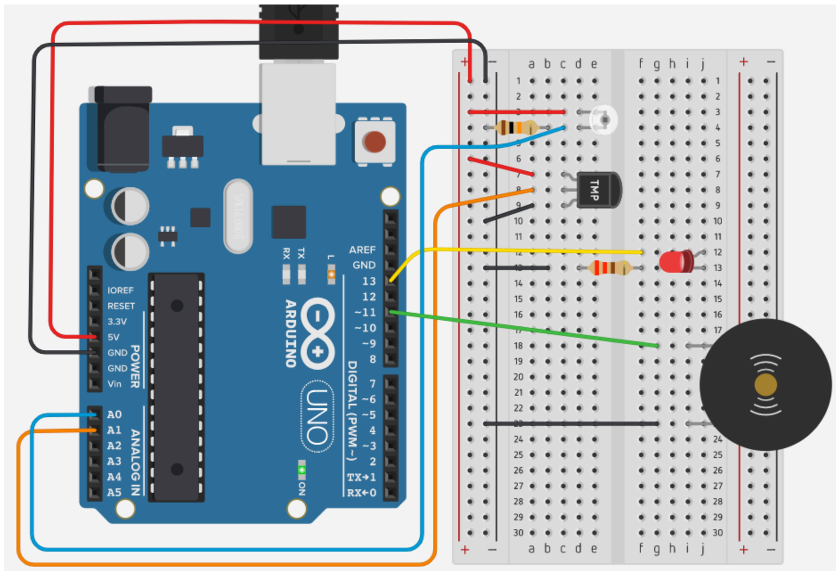

Figure 5: Sample student-created circuit in homework assignment on building and programming.

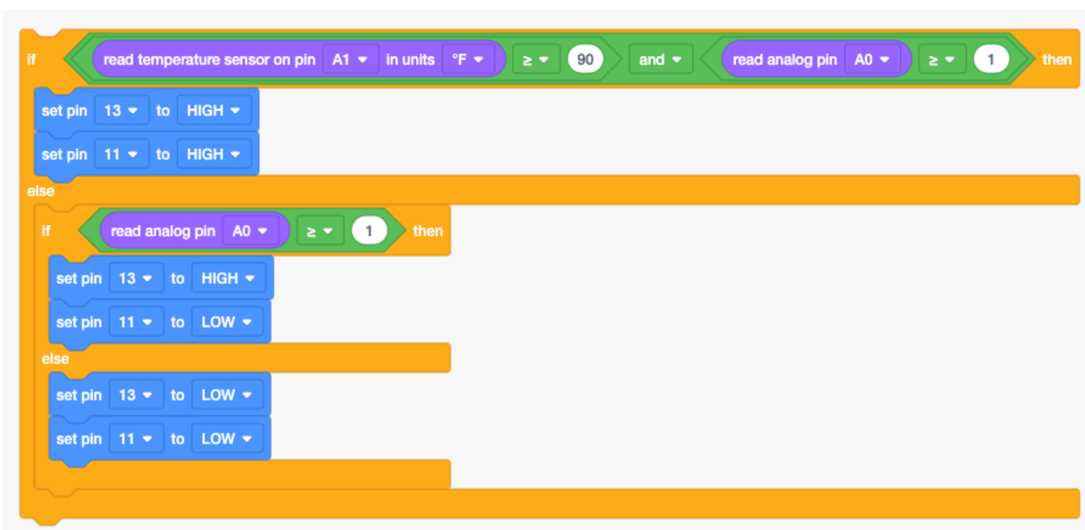

Figure 6: Corresponding sample student-created block code in homework assignment.

The student's written description of their creation in Figures 5 and 6 in this submitted homework assignment was: **"This is a sort of daylight intensity sensor. It consists of a temperature sensor and phototransistor as inputs, and an LED and buzzer as outputs. The phototransistor is connected to A0 as input, and out through pin 13 to the LED as output. If there is any light detected, implying that the sun is out here, the LED should light up. There is also a temperature sensor connected to A1 for input and pin 11 as output to a**

piezo. If it is bright out and it is hot, implying that it is a hot day in this scenario, the piezo buzzes (alongside the LED already being on due to light). I like to think of this as a circuit yelling at you to drink water."

Student electronics designs and code (block or typed) for their final group projects in the course are slightly more complex than the one-week assignment sample shown in Figures 5 and 6, but the final project is a group effort and teams are given over a month to develop that larger human-centered functional prototype and report.

Quantitative Analysis of Impact of Virtual Tool

Throughout the semester in Engineering Design & Society, all students were given the choice on any programming or circuit-based design, to either use the integrated block coding within the Tinkercad circuits platform, or to type out their code in the Tinkercad circuits platform, based on their personal preference and comfort level with programming.

At the end of the semester, to analyze the use and impact of the incorporation of the Tinkercad Circuits Virtual tool in parallel with the physical Arduino kit, course students were asked to reflect on the semester assignments and human-centered design projects about which option they ended up using more, Block Coding or Typed code. Results in Figure 7 show 62% of first-year design students decided to use the integrated block coding option, over the 38% that decided to type their programs in the Arduino programming language.

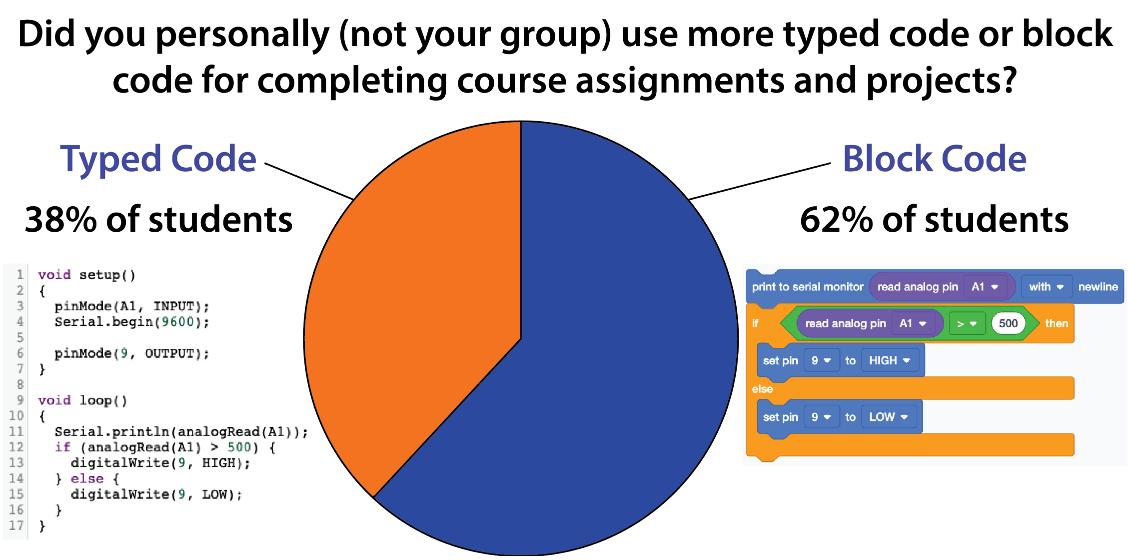

Figure 7: Percentage of students using Block Code versus Types Code in course.

The data of 62% of students choosing the block code option for use in first-year design reflects strongly that the added incorporation of the Tinkercad Circuits and block-coding option gave a desired choice for students to program and control their sensors and actuators through Block Coding. This supports one of the learning outcomes of the course, that all students participating, regardless of programming knowledge coming into the course, develop some individual knowledge of how to connect and control engineering based sensors and actuators for design prototyping.

Students were asked a second Likert-based question at the end of the semester to see if they left the course with enough working knowledge to control engineering sensors and actuators independently (regardless if they chose block or typed code). Figure 8 shows results to the question where students chose how much they agreed with the statement **"I have enough working knowledge of Arduino electronics to independently create a circuit with a few sensors and actuators and control it using code"**. The importance of this question is to examine if, with both Tinkercad Circuits in parallel with the existing student Arduino Kit, first-year students are developing enough independent creation knowledge from this portion of the course to begin to create engineering electronics for future design teams, internships, other courses, etc.

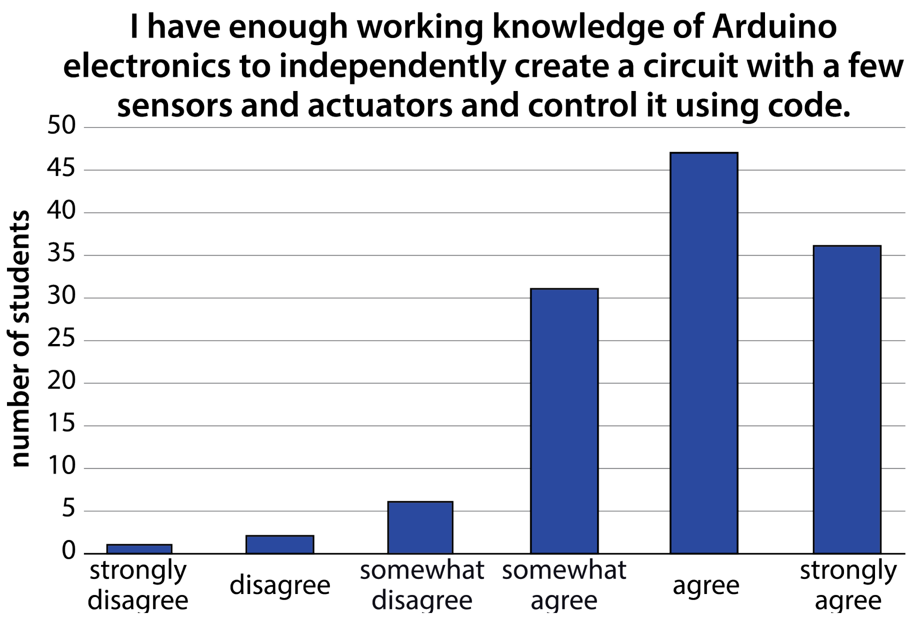

Figure 8: Student responses regarding working electronics knowledge at end of course.

The student data shows that the majority of students somewhat agreed, agreed, or strongly agreed with the statement they had enough working knowledge to independently create functional sensors and actuators systems controlled via code on their own. The student responses were given a weighted value of 1-strongly disagree, 2-disagree, 3-somewhat disagree, 4-somewhat agree, 5-agree, and 6-strongly agree; the weighted average of the scores was 4.9. This positive self-reflection learning outcome was especially meaningful given data was taken in a semester where students were fully online given the COVID crisis for this normally hands-on makerspace based course.

Qualitative Analysis of Impact of Virtual Tool

In order to look further qualitatively at the impact of the addition of the Tinkercad Circuits virtual building tool in the course to supplement the hands-on Arduino microelectronics kit, we asked students at the end of the course to reflect on the following question: **"What is your opinion of the Tinkercad Circuits virtual tool as a way to introduce Arduino electronics**

and block coding/programming for controlling sensors and actuators as part of this design course?"

The resulting narrative responses from students were too numerous to list in their entirety within this paper, but were analyzed and grouped into six categories of responses, with representative student quotes in each of the a) through g) categories of replies below to the qualitative analysis question.

a) Test and Debug Virtually Before Physically Building

One of the original intents of the addition of the Tinkercad Circuits software into the course was to empower first year students with the ability to virtually build and debug their wiring and/or code to run their inventions in virtual simulation and work out any issues before physically building the electronics with their hands-on Arduino kit. Some representative student responses to the open ended qualitative question that reflect this test and debug outcome include:

"I liked using the Tinkercad circuits and thought it was extremely useful for testing out builds and codes. It's especially useful when one does not have all the physical components they need (though I found it more satisfying to physically build the circuits). As for the coding aspect, the block coding worked well for me since I do not have a lot of coding experience, though I did usually look at the regular coding after to try to learn more."

"I think it was a great tool to help virtually design and program Arduino, because it allows you to build circuits and test them out to make sure there are no errors or mistakes, which will prevent you from damaging your circuit components when you build your projects in the real world. The block coding aspect also helped make it easy to program for beginners with no experience in Arduino code."

"I really liked Tinkercad because it gave me the freedom to test out Arduino builds and the block code in tandem before making it using the physical parts. It gave me more freedom to explore the different parts and parameters without feeling restricted in the more tedious physical building process. I also liked how I could run a simulation to ensure that my code was functioning the way I intended it to."

"I think it's convenient to test and make sure everything works before moving on to the physical build. It makes debugging easier and it really bridges the gap between not knowing anything about Arduino to understanding some key concepts regarding the Arduino"

b) Block Coding for Non-Programmers

Engineering Design & Society is a first-year course that does not expect any previous programming knowledge. Programming to control the sensors and actuators is a small section of the semester, and each student will have at least one full semester programming course in their respective majors later in their degree progression. The use of the block programming option within Tinkercad circuits allows faculty to structure a two-week combination lesson in Arduino compatible sensors & actuators with overall programming logic and structure in an easy to use form, without the need for teaching Arduino specific syntax. Students were given online videos explaining programming using block code in Tinkercad Circuits, and live build-along activities were completed with the professor. Students with previous programming knowledge were also shown resources for programming in the Arduino language if they preferred to use typed coding instead of the block coding. This parallel block and typed coding mode within Tinkercad Circuits allowed students to choose that path they were most comfortable with for controlling their physical Arduino-based sensors and actuators with the goal of including all students regardless of their previous programming knowledge. Representative student responses to the open ended qualitative question that focused on the Tinkercad Circuits block coding option include:

"I really enjoyed using Tinkercad both because of the way you could identify problems before physically building it and the ability to code through the block coding. As someone who has no prior coding experience, the block coding was a great way to still be able to create cool things and make the code to go with them."

"Using Tinkercad [Circuits] made it easier for people like me who have little experience with programming to be able to easily add code to a project. Without the use of this website, I am not sure how I would have been able to do any of the coding portions of the course."

"I found the block coding way easier to build and to derive a code versus using the Arduino program itself. Coding is really specific with every period, parentheses, etc., and if you miss something, your code doesn't work. With Tinkercad [Circuits], you were able to practice coding without having to worry about all the minor details. It's great for getting the general idea, then after we master what general coding components or ideas are needed for our circuit, then we can learn the details for the Arduino program. It's like Duplo Lego blocks for programming versus the Legos that have a thousand pieces."

"I really liked the use of the Tinkercad Circuits virtual tool as a way to introduce Arduino electronics and block coding/programming for controlling sensors and actuators. It helped me to understand the concept of coding, as I had no previous experience before this class. I found it easier to handle the Tinkercad circuit tool than the Arduino electronics at first, before I began to understand the process of coding/programming."

"I think that the block coding on Tinkercad Circuits was very useful for me especially since I was just beginning to code. I used the block programming option on Tinkercad for every assignment that needed code. I also thought that using Tinkercad made programming and creating things on Arduino easier because I could redo wiring or the code quickly whenever I saw that the simulation did not work the way I wanted."

c) Faster Way to Build and Test Prototype Ideas

Tinkercad Circuits allows quick virtual wiring of components and adaptation of code (block or typed) to then virtually run the code to control sensors and actuators in simulation. This allows students to test and change their ideas quickly in simulation before physically wiring them with their Arduino Kits. Representative student responses to the open ended qualitative question that related to the use of the virtual tool for rapid prototyping include:

"The Tinkercad Circuits helped me mess around with different designs so much easier than if I built it in real life. The block coding helped me understand the code so much more than I would had. Overall, having Tinkercad Circuits helped me learn so much more about circuits and coding than I would had if it was not available."

"I think Tinkercad [Circuits] is a great introductory tool to Arduino. While I do not think it should replace the physical construction of the Arduino project entirely, I think it can be a great tool for quickly testing prototypes. While I personally do not like block coding, I understand that it can help those who are not familiar with coding."

"I loved it! It was easier to trouble shoot in Tinkercad than in real life, and thus easier to learn the pieces."

"I think it made things a lot easier to understand and work with. Being able to problem solve on Tinkercad made things a lot easier as I was not having to deal with the components in person. Also you could easily change the code and see how it changed the project much faster."

"The Tinkercad Circuits is so very helpful for the course, if you do not want to spend hours connecting each wire and then all of that for it to not work, the Tinkercad circuits are such a helpful way to ensure that you don't have to spend hours and you can be confident in your design before you make it in real life."

d) Convenience Factors & Team Virtual Collaboration
When students don't have their physical Arduino kit handy the Tinkercad Circuits tools allows them more convenient access to prototyping until they are able to access their physical Arduino kit. Using a virtual tool to work on the functional electronics portion of a team design project allows multiple team members to see and experiment collaboratively with the sensors, actuators, and code, without having to be in the same physical space sharing and re-writing a physical kit. The use of the virtual tool proved useful in team collaboration in the design and planning stages of team prototyping. Typical student responses to the open ended question that conveyed the convenience and team collaboration factors include:

"I liked having this as an option in case I was studying or doing work somewhere where it would be inconvenient to carry around my whole Arduino kit. It was also a good practice to lay out designs before we actually built them because there was no error or frustration when things were not going into the spot they were supposed to."

"Tinkercad circuits is convenient for group projects that have to be completed online due to distanced learning. it allows for the entire group to see and interact with the circuit themselves rather than one team member building the circuit and others relying on pictures or recreating the circuit for themselves."

"I think Tinkercad Circuits was a great incorporation into the course because it made it more accessible to learn about the Arduino kit without having to physically use it all the time. Furthermore, using a virtual tool allows more flexibility to the student; they do not need to have the Arduino kit by their side all the time."

e) Online due to COVID Virtual Tool Advantage
The semester that this research study occurred was during the COVD pandemic when Engineering Design & Society, a hands-on makerspace course, had to be converted to a fully online delivered course. The Tinkercad Circuits tool was useful in this temporary online transition in allowing a convenient way to still incorporate active-learning and hands-on work for students while being constrained to learning in an online environment. Representative student responses to the virtual tool while leaning online due to COVID include:

"I thought Tinkercad was really helpful, especially in the COVID age. It helped us visualize what we wanted to build before we actually went through with it, so we didn't waste time assembling and re-assembling a physical circuit."

"I think the virtual tool was very helpful, and still allowed the assignments to feel hands on despite being online."

"I believe that Tinkercad Circuits was a valuable virtual tool to have as a way to introduce the Arduino electronics and programming for circuits. This allowed teams to work remotely this semester but will allow future in-person semesters to use Tinkercad to test their final design projects and circuit assignments before physically constructing them. I do believe that working with the actual Arduino kit is a more valuable and fun experience than Tinkercad, but Tinkercad does provide a good start for students with little to no programming experience and will help in future Final Design Projects."

f) Virtual Tool for Confidence Building in Sensors & Actuator Use
One aspect that was revealed through the student open responses to the qualitative question was the utilization of the Tinkercad Circuits tool helped students, especially those with no prior making experience, build self-confidence in their abilities to learn the material and begin to create electronic systems independently. Typical student responses reflecting on this self-confidence building include:

"Tinkercad was perfect. It made understanding the code and building the circuit so simple and understandable regardless of prior knowledge."

"I think [Tinkercad Circuits] was really effective to introduce circuits. I had no prior experience with programming or circuits and was able to understand and build my own system."

"I think that this was a very useful and helpful tool as it made learning the board much easier than connecting and disconnecting wires at random on the real board. It likely helped me to avoid breaking parts or over twisting wires as I was able to get a feel for what I was doing before building so that I didn't shove pieces on at random and mess up the real board."

"Tinkercad [circuits] worked well as tool for becoming familiar with the Arduino components and I also found it to be beneficial because it had other sensors and actuators that did not come in our kits. I also felt like it was better to be able to code it ourselves in Tinkercad rather than

just have the code given to us with the Arduino software and felt like I gained more from doing it on my own."

"I felt that the use of Tinkercad was extremely effective at introducing the functions of different Arduino components. Being able to see the effects that the different components and coding had on the simulation helped me learn more about how circuits work and how to control various inputs and outputs. I definitely think that Tinkercad should continue to be used in this course."

"I liked the Tinkercad Circuits virtual tool and thought it was a good introduction to Arduino electronics. It was also less intimidating than the physical circuit."

"The virtual tool helped a lot in understanding and testing the code- I think it helped me visualize the process better and I felt more comfortable and confident in actually building the physical circuit."

"Tinkercad was very useful in introducing these concepts. Instead of just being thrown into Arduino with only the handbook to guide me, I instead was able to work on virtual circuits that I could make work without a lot of focus on the specifics of the code."

This one response from a student to the open-ended question gave an accurate overall summary of the original intent of the addition and use of the Tinkercad Circuits virtual tool in collaboration with the hands-on Arduino electronics kit: ***"I think the Tinkercad Circuits Virtual tool is a great way to introduce Arduino electrons and block coding for controlling sensors and actuators for this design course. It's simple enough that students unfamiliar with the topic can learn and develop new skills while it is adaptable enough for the more experienced students to go outside the class expectations."***

Conclusions

Reflecting upon the results of this one semester study of the integration of the virtual Tinkercad Circuits tool and the physical Arduino electronics kit, a few general trends emerged. Block Coding was utilized by 62% of the first-year students over typed programming. The addition of the Tinkercad Circuits platform provided a viable option for first-year students with little or no programming knowledge to be able to still independently create and control sensor and actuator based circuits. The collaborative use of the Tinkercad Circuits platform side-by-side with the physical Arduino kits returned six advantage areas based on the student qualitative analysis.

The areas students found benefit from the virtual tool addition were:

a) Test and Debug Virtually Before Physically Building
b) Block Coding for Non-Programmers
c) Faster Way to Build and Test Prototype Ideas
d) Convenience Factors & Team Virtual Collaboration
e) Online due to COVID Virtual Tool Advantage
f) Virtual Tool for Confidence Building in Sensors & Actuator Use

Based on this research study, the Tinkercad Circuits tool and block programming modules are now part of the standard curriculum within Engineering Design & Society to use in conjunction with the hands-on Arduino Kits. The incorporation of this virtual tool will hopefully continue to promote a course environment with equal opportunity and access of tools for all first-year students regardless of previous programming experience. The end goal is for all students to be able to control electronic sensors and actuators as part of their human-centered prototypes in this course, and then have confidence to continue using and expanding those skills in their future engineering design experiences.

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