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Using Tinkercad in introductory electrical and computer engineering courses

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Using Tinkercad in Introductory Electrical and Computer Engineering Courses

1. Introduction and motivation

Over the last several decades, engineering programs have started adding introductory engineering courses that do not rely on a long list of prerequisites, such as physics and calculus. This was done for many reasons, such as making engineering more attractive, improving student motivation, and increasing retention. For example, in our electrical and computer engineering programs, we added a full year of introductory courses, covering areas such as exploration of the field of electrical and computer engineering, circuit analysis, problem solving, programming, and combining software and hardware to accomplish a larger goal, usually as a part of a team project. Typically, these courses emphasize hands-on experience as a way to introduce various concepts.

This hands-on component can be augmented with appropriate simulation tools which have advantages such as simplicity of use, wide availability, and use across multiple courses. The use of virtual tools in engineering education has been recognized as an effective method for fostering learning in diverse engineering disciplines [1,2]. Circuit simulation tools like LTSpice from Analog Devices or Multisim from National Instruments or similar are widely used but they are typically introduced during the second-year courses on circuit analysis. However, introducing such powerful and complex tools at the first-year level is problematic. The complexity of the interface and conceptual difficulty of interpreting schematics and different types of simulations can be intimidating and demotivating for students who may be seeing this material for the first time. As stated in [3]

"*(SPICE-like simulation tools)* tend to provide a utilitarian user interface, with little emphasis on realistic depictions. This acts as a barrier to entry for novice users."

Recently, the well-known 3-D design tool Tinkercad from Autodesk was expanded to include simulation of electrical circuits [4-6]. The software is web-based and has an intuitive and informative graphical interface which enables its use even for middle and high school students. Its simulation capabilities cover areas that go well into the requirements of our usual circuits courses. What distinguishes Tinkercad from other circuit simulators is its built-in interface to Arduino and BBC Micro:bit microcontrollers which enables programming either in their native language (C-like for Arduino) or by using a special built-in graphical user interface that uses code blocks. This opens up opportunities for exploring not just analog and digital circuits but also microcontroller projects that include electrical circuits [7],[8].

Finally, one additional complication is that the prerequisites for our first introductory course are light and include only college-level precalculus courses which students can take or test out of.

While this removes some of the barriers discussed earlier, this presents a different significant challenge due to the wide variety of student backgrounds. Therefore, it is important to provide very substantial scaffolding for students with limited experience in technical areas while trying to provide enough challenges for the students with more relevant background. This problem is particularly important in programming, which is known to be challenging and potentially frustrating for students.

To address the issues mentioned above we have introduced Tinkercad as a tool to simulate both the Arduino programming environment and electric circuits, where it provides a realistic visual representation of the experimental environment. This approach is implemented in two programs: one in the United States and another in China. At both institutions the instruction is done face-to-face, and labs are used extensively. We are especially interested in addressing the following questions:

a) Student technical preparedness, both hardware and software (Are they ready?)
b) Student attitudes toward using Tinkercad (Was it helpful?)
c) Instructor observations and experiences (Is implementation hard? Do students benefit?)
d) Any differences between the two institutions in terms of student preparedness and attitudes

In our previous report [9], we have shown that most students have little background in either circuit design, hardware, or programming. However, there is a good number of students who are very confident in their abilities in these areas, which means that we have to accommodate a wide range of backgrounds and preparation to be sure to keep all students engaged. We have also found that students liked the Tinkercad software, but the sample was small. In this paper, we will present a more comprehensive set of data which enables us to draw firmer conclusions. Next, we will discuss the curricular context and how we used Tinkercad. This is followed by the initial assessment of the effects of Tinkercad introduction and conclusions.

2. Curricular and institutional context

Portland State University (PSU) is located in a major urban center and serves a very diverse population. This diversity includes many transfer, international, and non-traditional students. The academic year is based on 11-week long quarters, with the final week dedicated to final exams. In our department, students can attain one of two ABET accredited BS degrees: Electrical Engineering and Computer Engineering. However, these two programs are almost identical in the first two years.

Recently, PSU has started a partnership with Nanjing University of Post and Telecommunication (NJUPT) which is a large urban university in China. The two universities established an umbrella program commonly referred to as Portland Institute Nanjing (PIN). Within PIN, we have collaboratively developed two new engineering programs that are based on the electrical engineering and computer engineering programs at PSU. Teaching is done in both English and Chinese. There are several pathways for students to attain degrees from both institutions.

2.1 ECE 101 Exploring Electrical Engineering

In the Electrical and Computer Engineering department's first-year course students are introduced to this area of engineering gradually. The main objectives are to engage students in fun and educational projects, acclimatize them to campus life, and gently introduce more technical problems and lab equipment. More details can be found in our prior publications [10].

One key component of the courses is the labs which introduce students to the common lab equipment and instrumentation. Similarly, projects are essential, and students are given flexibility in the choice of topics. Learning outcomes for the course include the ability to:

1. Solve engineering problems
2. Perform research on areas of electrical engineering
3. Write technical reports and summaries
4. Perform basic lab experiments
5. Complete a project involving both design and technical elements
6. Work on a team
7. Recognize basic ethical issues

Many topics in the class are introduced lightly with the understanding that they will be explored more in-depth in the years to follow. The learning outcomes are accomplished through a series of in-class activities, formal laboratory sessions, and out-of-class projects. The lab sessions focus more on the education surrounding common lab equipment and instrumentation. Projects are team-based, with a prompt that allows choice for creativity and uniqueness while providing constraints. In-class activities are aimed at providing students with a starting point to labs and projects. The in-class activities and lab prep are where Tinkercad was mainly utilized in the course to help aid in their learning, as well as to add some depth and enable more student experimentation, as discussed in section 3.1. This course is followed by another two first-year courses that deal with programming microcontrollers in Python and C. These two courses follow suit in providing students with the opportunity to build on their skills of problem solving and teamwork.

2.2. PIN 101 Introduction to Computer Hardware

This course was developed in partnership with NJUPT in China and has the same learning goals and outcomes as the ECE 101 course taught at PSU [10]. While there are some content differences, the largest difference and challenge in this course is the scale: our domestic courses have enrollments around 40-70 students, while in China there are 240 students. Due to COVID-19 restrictions, course lectures were initially delivered online from the US while labs were done in person. However, in the fall of 2024 the course was delivered fully in person.

Labs form an essential part of the course: three are related to electric circuits and two deal with Arduino Uno. The first three support the introduction of concepts such as resistive circuits, Ohm's law, voltage and current dividers, and time-dependent R-C charging. These topics are selected not only because of their fundamental nature but also because the math and physics involved can be developed intuitively. Arduino Uno has been used extensively to introduce programming and hardware interfacing, and we cover only the basics that require only minimal experience with programming. However, this is enough to enable students to pursue more ambitious projects involving multiple sensors and actuators. Given that students come with a wide variety of experiences in this area, we have to be very flexible in terms of difficulty in the final projects that use Arduino.

3. Why and what of Tinkercad

Tinkercad is a free, web browser-based app that covers 3D design, electronics, and coding [4]. It started as a 3D modeling tool used in conjunction with 3D printers. Electronic circuit simulation was added in 2017. While the app can be used by anyone with a web browser and internet access, it has special features that make it accessible for K-12 use and it was initially aimed at middle school and high school students. As the Tinkercad modeling program continued to grow, Autodesk, in 2018, implemented the output feature for their more sophisticated software. Now students can build in Tinkercad and output their work to Autodesk Fusion, a more industry level software. Similarly, for their electronic simulation, students can also export to Autodesk Fusion, as well as export a .BRD file to open in PCB design software such as Autodesk Eagle. This is a great feature that allows students to see the next step in their work in the industry world.

Currently, the app supports Arduino Uno and Micro:bit microcontrollers. Programming is done either through a graphical interface called CodeBlocks, again aiming for K-12 users, or through a text-based interface. Microcontrollers can be interfaced with electronic circuitry so that code development can be done in parallel with hardware development. Figure 1 illustrates the equivalence between the simulation and actual circuit (taken from [6]).

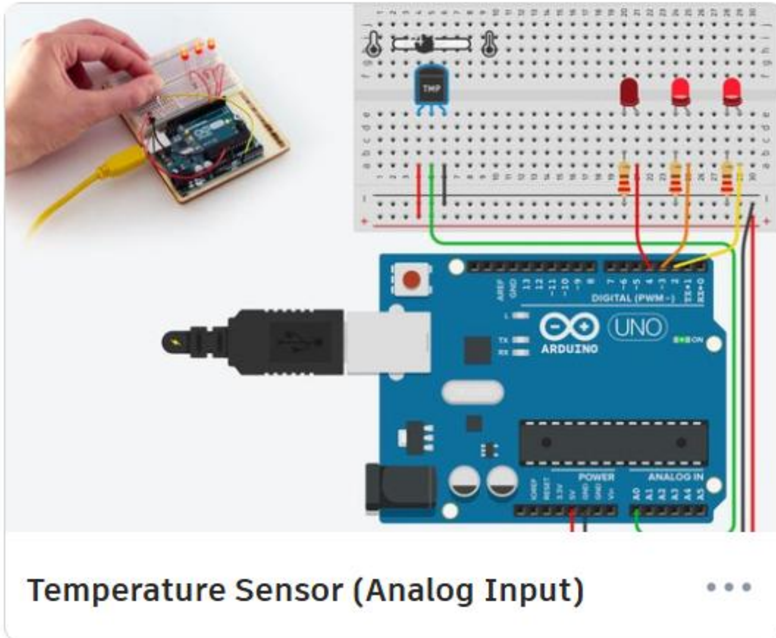

Figure 1. Illustration of simulation and implementation of a temperature sensor [6].

Extensive literature on projects using Tinkercad already exists, both in print as well as video tutorials. In our context, we want to explore using it to lower the barrier to engaging in authentic engineering projects. We hope this will happen through:

A. App that is easily accessible from anywhere
B. Intuitive interface that closely mimics real-life hardware
C. Early involvement in combined hardware and software projects
D. Combining the simulation with building projects in the lab and testing them in real life

Next, we discuss how Tinkercad is currently used in our ECE and PIN courses.

3.1 Implementation in ECE 101

The ECE 101 course is a level-one introductory course with light math prerequisites such as functions and trigonometry. It is typically taken by Freshman in their first quarter at PSU. Therefore, the course has the challenge, as discussed above, of a wide range of student backgrounds in math, science, writing, reading, etc. This course therefore tries to instill common practices and knowledge that will be needed in the years to come. This leaves the course with a wide range of topics including career paths within electrical and computer engineering, research and writing as a scientist, digital electronics, “engineering math,” and engineering ethics.

The electronics portion of this course is the area that utilized Tinkercad. The students have a separate laboratory section for the lecture. The electronic topics of the lectures and labs combined are as follows:

1. Ohm's law
2. Sensors in series and parallel circuits
3. Capacitive and Inductive circuits
4. Transistors
5. Logic gates and ICs
6. Arduino
7. Variable Power Supply
8. Time-Varying Signals

Tinkercad was first introduced during lecture to have the students set up an account and join the class online where activities could be assigned for completion. The first activity was just introducing the basic components of a circuit: a power source (battery), a bread board, wiring, a load, and resistor, as well as a multimeter. This setup can be seen in Figure 2. Students were given the activity with components not placed together, Figure 2a and a schematic to follow, Figure 2b, to build the simple circuit in Figure 2c. For many of the students this is their first experience with even the simplest circuitry. Many students had difficulty navigating the interconnections of the breadboard, as well as the anode and cathode of the LED. This in-class activity was done in the same session as discussions on "what is electricity and electronics?" which included the topics of resistance, resistor values, and electrical engineering tools (such as the multimeter).

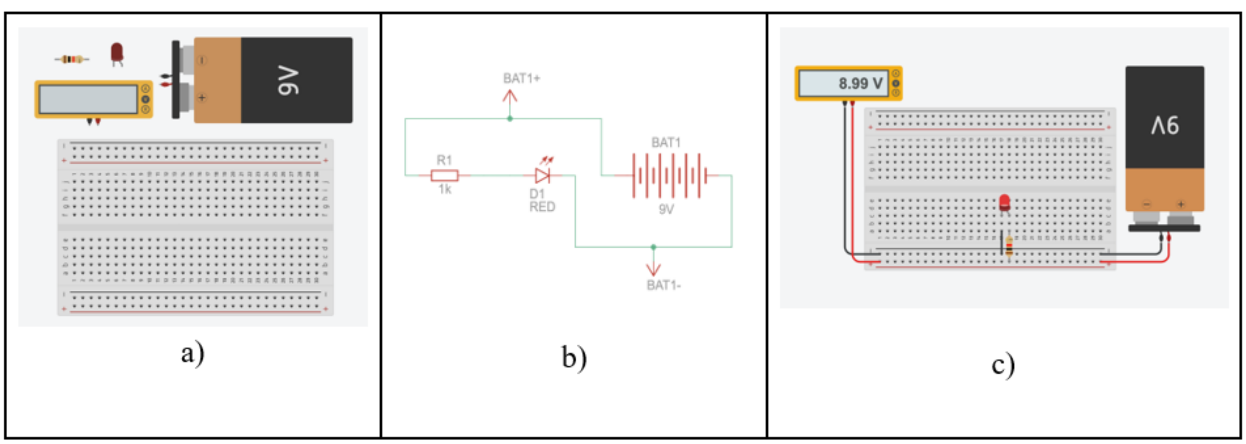

Figure 2. Setup of a basic circuit with a load and resistor and measuring voltage in Tinkercad: a) setup given to students to tinker, b) schematic for students to follow for setup, and c) final basic circuit simulation.

As the course progressed through the topics discussed above, the lectures would include a Tinkercad activity to complete together with discussion. This included activities with multi-load circuits in series and parallel, implementing switches and potentiometers, demonstrating the polarized capacitor, introducing transistors as electric switch, and creating ICs. Some of these completed activities can be seen in Figure 3.

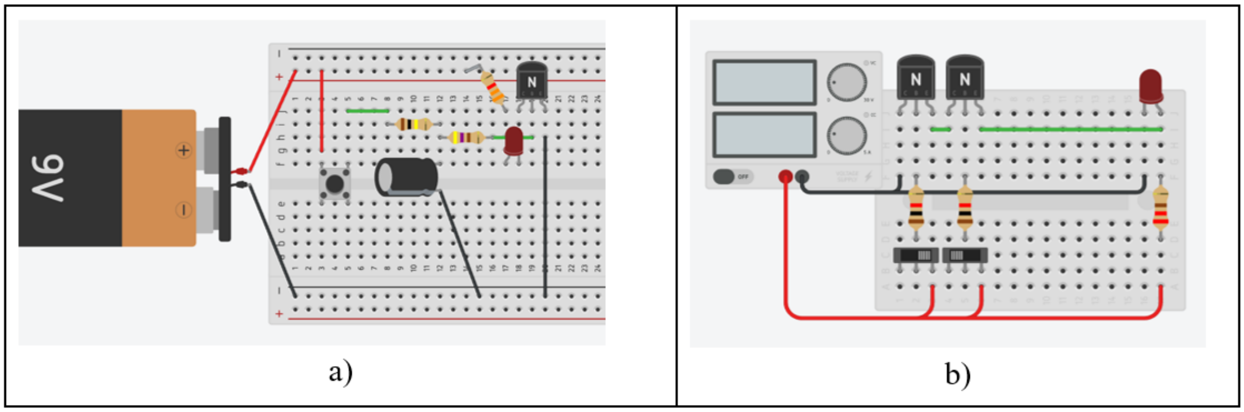

Figure 3. In-class completed Tinkercad activities: a) The Very Slow Light Build - demonstration of the capacitor in working with a transistor to very slowly dim an LED with removing the power source, b) The NAND gate - demonstration of how transistors build to form logic gates, and eventually ICs.

In addition to the in-class activities Tinkercad was used within the labs both as prep work beforehand and validation during lab. Figure 4 demonstrates students' work of the Voltage Divider Lab where students were required to build an LTSpice and physical model. However, many student groups also built the circuits in a Tinkercad simulation to validate their findings as a "physical model" before building on the protoboard.

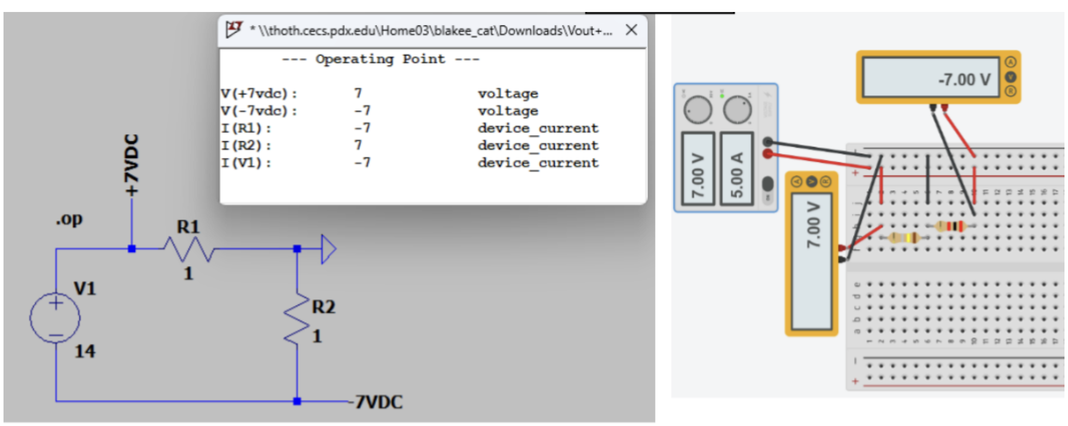

Figure 4. Student's work for the Voltage Divider Lab, in LTSpice (left) and Tinkercad (right).

3.2 Implementation in PIN 101

This is the first engineering course in our PIN program in China and does not have any formal math or physics prerequisites, though students are taking calculus and linear algebra courses in parallel. In order to get to more interesting design and project-based problems we have to first cover a few circuits basics, such as resistive circuits and voltage and current dividers. Next, we bring up time-dependent circuits through R-C charging, which then naturally leads to applications of NE555. In NE555 timer circuits, charging of R-C networks and use of voltage dividers are essential features.

However, the math and physics required for explaining these topics is relatively straightforward and can be built intuitively. This approach is reflected in the selection of lab topics which are then followed by applications, such as using a timer IC NE555. While these applications may look intimidating at first glance, they require only a handful of components. Students can relatively easily build practical circuits to measure unknown capacitance or produce a blinking LED. This led us to develop three labs dealing with:

1. Ohm's law and resistive circuits
2. Observing R-C charging and discharging
3. Implementing astable (oscillating) circuit using NE555

This course also covers very basic programming of Arduino microcontrollers. Students are taking a C-programming class in parallel which makes this a little bit less challenging. We provide a lot of examples that students can reuse with little modification. This has led to the development of two Arduino-centric labs dealing with handling sensor data and controlling actuators. Students also work on teams to complete a very short "micro" project that combines two or three components with Arduino.

In the last two years, in addition to the lab sessions we added a formal requirement for pre-lab exercises. This was prompted by two realizations:

A. Many students came to labs without doing the required reading or watching videos
B. It is possible to almost exactly replicate the lab content on Tinkercad.

Once we realized that point b) was possible it was fairly straightforward to design pre-lab assignments that required completion of Tinkercad simulations of some fraction of the actual lab assignment. For example, the second lab is about observing R-C charging. In the lab students build a simple circuit on the breadboard while the same circuit is simulated in Tinkercad, as shown in Figure 5. The simulation also enables asking "what if" questions that may be too time consuming in an actual lab setting. We believe that the fact that the simulation directly illustrates the actual experiment is very important because it reduces the cognitive load for novices. For example, by initially working with realistic graphical representations of circuits, students do not have to learn all the intricacies of circuit schematics.

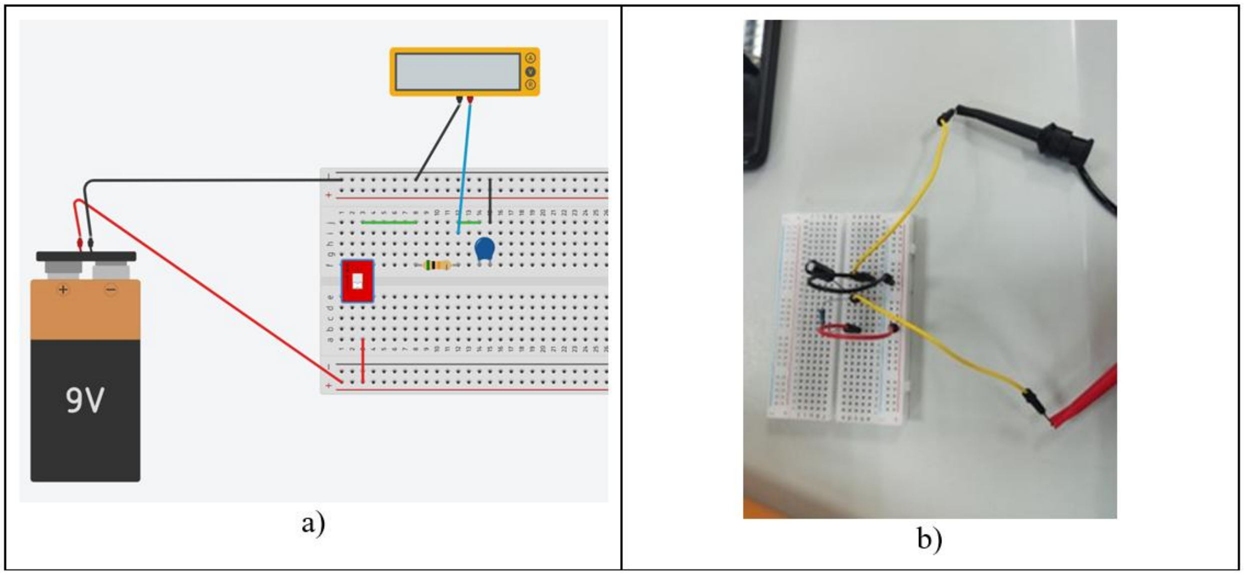

Figure 5. Setup of a R-C circuit and measuring capacitor voltage: a) simulation using Tinkercad, b) measurement in the lab.

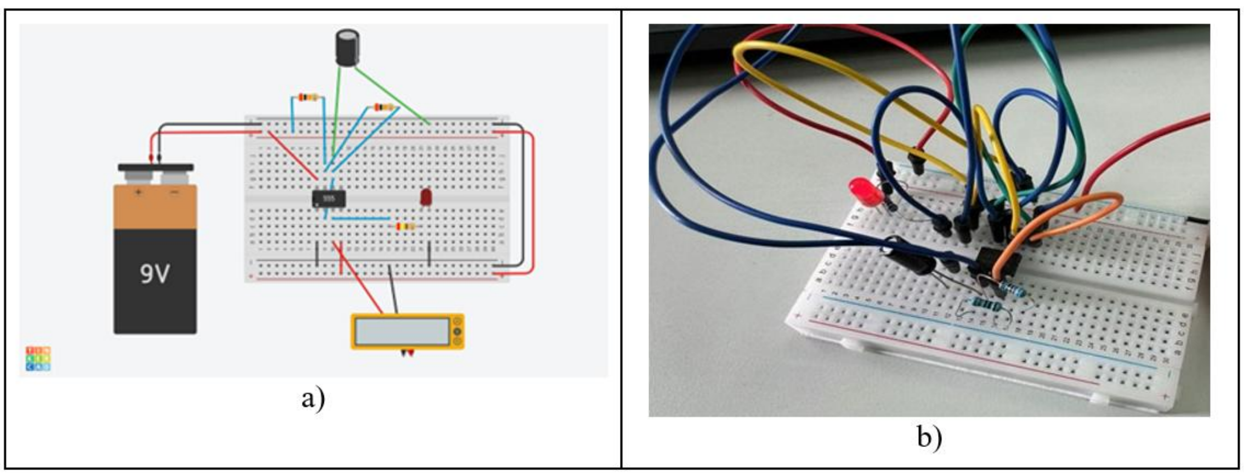

Figure 6. NE555 astable circuit a) simulation in Tinkercad, b) lab implementation.

Another lab experiment that is surprisingly easy to do in Tinkercad is simulation of the astable operation of an NE555 timer, which is shown in Figure 6a. In simulation, it is easy to adjust components and directly observe the effects of various variables. Once a buzzer or LED are attached as loads, these can be easily observed in either simulation or in the lab. Note that the NE555 operation is based on two concepts that were introduced in the two previous labs: voltage division which is used to set thresholds, and R-C charging which sets the frequency of pulses. Even though students come well prepared for the lab experiment, this is still a challenging experiment mainly because it requires attention to details in wiring and debugging, as illustrated in Figure 6b.

In the future, we will add one more Arduino-based lab and will try to coordinate better with the C-programming class. As is well known, students tend to compartmentalize knowledge and need guidance to apply it outside of the given classroom.

4. Assessment

Assessing learning gains due to a given intervention is notoriously difficult. Therefore, in this initial examination of our use of Tinkercad we are only addressing:

a) Student satisfaction and self-evaluation - evaluated through surveys
b) Earnestness in completing tasks - evaluated through completion of non-graded assignments
c) Use of Tinkercad outside the classroom - evaluated through student use in final projects

In our previous report [9], we presented the results of a brief survey in the follow-on course taught at PSU. Here, we present the results of the same survey at the end of both ECE 101 and PIN 101. The questions used are the same and are listed in Figures 7 and 8. In ECE 101 only 15 out of 73 students filled out the survey while in PIN 101 115 out of 239 students did the same. The relatively low response rate of 20% in ECE 101 makes conclusions tentative but it provides us with a baseline for future improvements.

PIN students seem much more enthusiastic, judging by the number of those who Strongly Agree. Two questions seem to stand out:

a) Tinkercad improved my motivation to study
b) Tinkercad was useful to prepare for labs

PIN students thought that Tinkercad was useful as preparation for the labs more strongly than ECE students. This can be attributed to the more formal preparation for the labs in PIN 101 which was done via Tinkercad based simulations. In ECE 101, Tinkercad was used primarily during in-class instruction. During classes students were happily engaged with the program with natural frustrations of learning something new. However, it is possible that the "lab prep" portion of using it may have felt like it was unnecessary duplication.

Interestingly, ECE students were also less likely to agree that Tinkercad improved their motivation to study ECE. This will require further research because student motivation has a large impact on their learning. Students in both courses are in agreement in the remaining five questions and believe that Tinkercad was easy to learn, and that it improved their understanding of circuits, Arduino hardware, and Arduino programming. They also would like to continue using it. Our previous survey of ECE students produced similar results where we observed that students liked Tinkercad's ease of use and its usefulness in learning different concepts. In that survey, almost 80% of students agreed strongly that it is useful in introducing Arduino and Arduino programming. Similar results were reported in a recent study where students found Tinkercad easy to use, and they enjoyed using it [3].

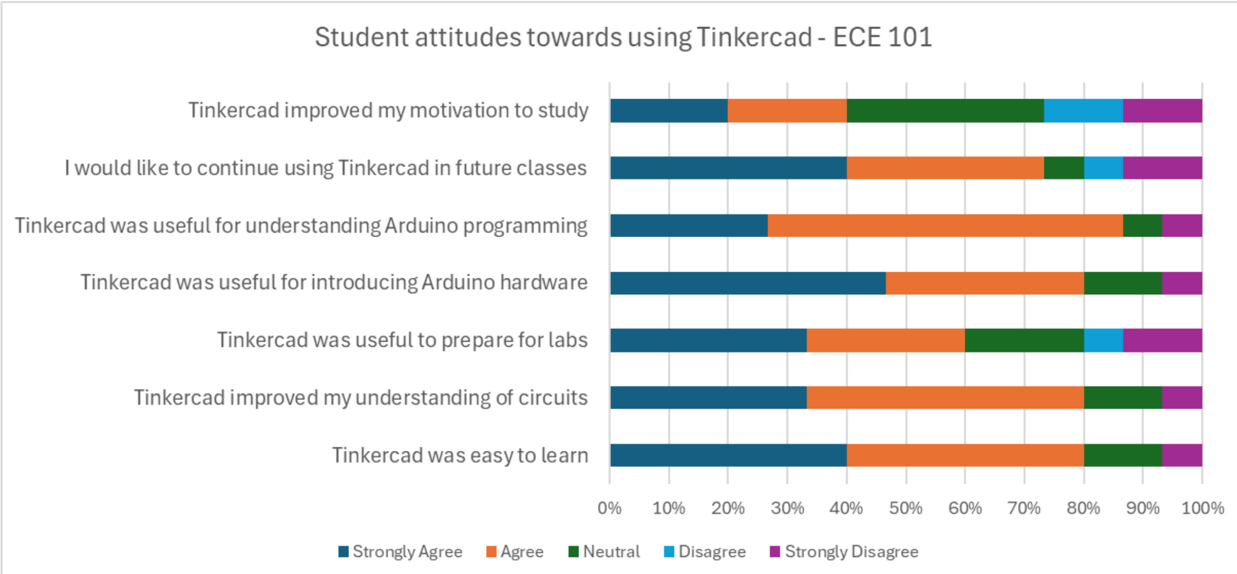

Figure 7. Tinkercad usage satisfaction survey results. ECE 101 course taught at PSU, Fall 2024. The total number of respondents is 15 out of 73.

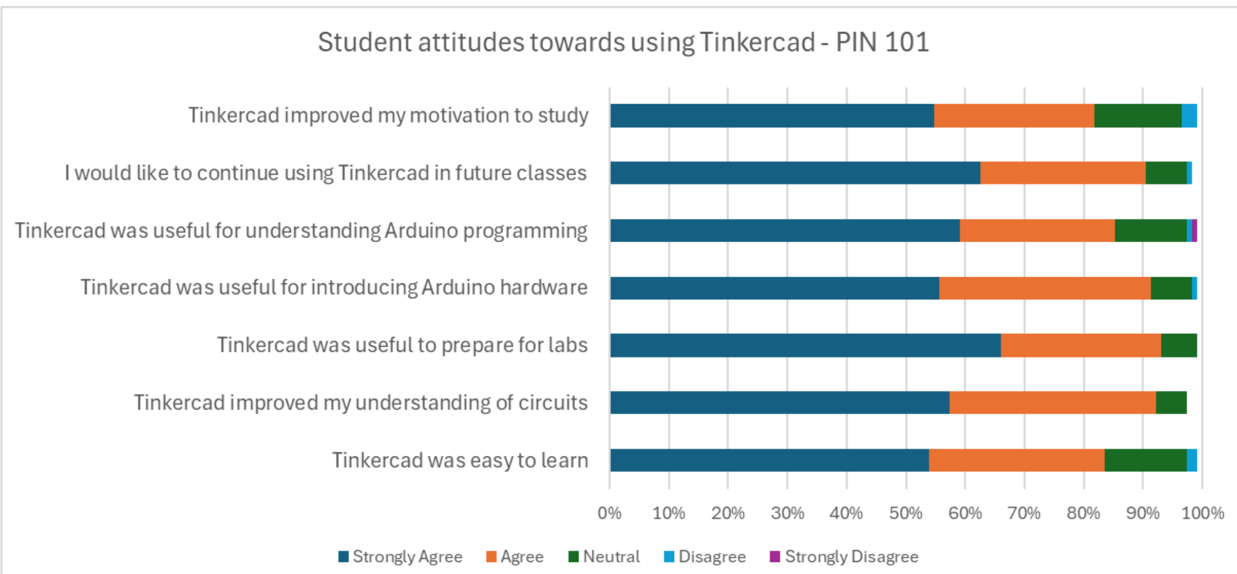

Figure 8. Tinkercad usage satisfaction survey results. PIN 101 course taught at NJUPT, Fall 2024. The total number of respondents is 115 out of 239.

Another way to gauge student interest or earnestness is to look at how many have completed the pre-lab assignments in PIN 101. Note that these were not graded nor were they included in the overall score. Instructors strongly encouraged students to do them, but they were not rewarded for completing them. Completion rates for the four pre-lab assignments are shown in Figure 9. Overall, these results are encouraging but we will try to improve them further.

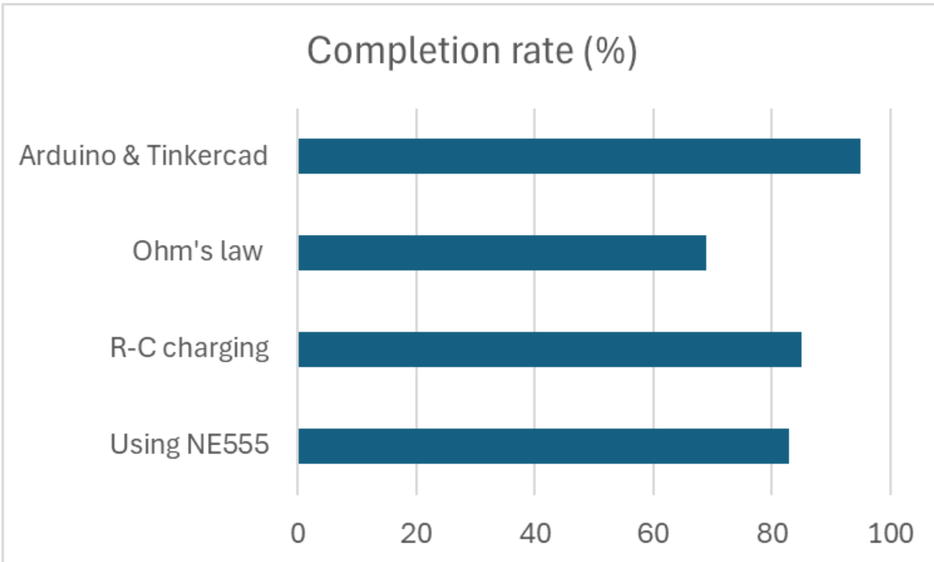

Figure 9. Completion rate of pre-lab assignments consisting of simulations in Tinkercad. The total number of students is 239.

As discussed in section 2.2 above, in the PIN course students work on the final project that involves a microcontroller. The default choice of the microcontroller is Arduino because that is what students are trained on in our lab sessions. However, a significant number of students have experience with other microcontrollers, especially STM32, from their high schools. We investigated how many teams used Tinkercad in the design and implementation of their projects and the results are presented in Table 1. We judged this by looking at the reports and searching for the keyword “Tinkercad”. In addition, we checked the figures included in the report to see if they were screenshots of Tinkercad. Note that the project description did not mention Tinkercad at all so its use was entirely up to the teams. We believe that this level - roughly one third of students - is a good indication that students found Tinkercad useful.

Table I. Usage of Tinkercad by PIN 101 teams during their final project.

	YES (# of teams)	NO (# of teams)	Using different microcontroller (# of teams)
Using Tinkercad in the final project report	11	30	8

The ECE 101 course has a long-term project component. This term the final project was to build an automated Rube Goldberg machine. While the ECE 101 course does not directly cover microcontrollers in content, many of the final projects involved microcontrollers. Tinkercad, having an introductory user interfacing, was utilized in 50% of the student projects. This value is just what is reported in the student final reports and presentations. In the final project reports, many demonstrated the use of Tinkercad as a way to brainstorm, plan, and simulate before buying and building a physical prototype with electronic components. “Thankfully, Tinkercad was a super useful tool when we built and rebuilt the system of the design,” a student stated in their final report when discussing the implementation of a moisture sensor.

5. Conclusions

We have completed several rounds of introducing Tinkercad in introductory electrical and computer engineering courses. This was done in two very different curricula and institutional contexts: one in the US and another in China. It was first introduced as a complementary activity, building circuits first in simulation before building them in the lab. Secondly, we introduced it as a first step in learning to program Arduino microcontrollers. Both of these were successfully implemented.

Results of the most recent survey indicate that students appreciate its ease of use, intuitive interface, and opportunities to experiment on their own time and outside of the lab. Students in China were more enthusiastic about its use as preparation for the labs and its effect on their motivation to study. The former result can be explained by the different uses inside the two classes. In China there was more formal preparation for the labs, which was done via Tinkercad-based simulations. In ECE 101, Tinkercad was used primarily during in-class instruction. The latter result regarding motivation will require further study. In the PIN 101 course, roughly one third of the student teams used Tinkercad in their projects even though it was not required. Similarly, one half of the students in ECE 101 utilized Tinkercad at some stage of their final projects. This further confirms the conclusion that students have indeed found Tinkercad useful.

While these initial results are very encouraging, there are still many open questions, such as what the longer-term effects of Tinkercad are and how it integrates with other, more advanced tools that are introduced in follow on courses. To address this, our future plans include expanding the programming component, exploring ways to integrate it better with follow-on courses, and developing appropriate assessment tools.

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