Hands-On Science Activity in Digital Circuits for High School Students

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1. Abstract

Many students do not consider an undergraduate degree in engineering because they don't know what engineers do, they have little knowledge about engineering coursework, or they don't believe they have the requisite skills to pursue this pathway. In electrical and computer engineering programs, this is especially true for female students and students from historically under-represented groups. The INVESTING NOW program at the University of Pittsburgh encourages the development of hands-on science activities for area high school students from these groups as a way to increase their participation in STEM education. We describe an activity conducted by the Department of Electrical and Computer Engineering. The goals are to expose participants to the field of ECE, have them complete an activity similar to a sophomore-level digital circuit laboratory experiment, and use that success to demonstrate that they possess the skills necessary to pursue an engineering degree.

The activity begins with a brief introduction to fundamental concepts in digital circuits (voltage, current, binary representations), after which the participants use an oscilloscope to measure the calibration waveform, and consider it as a model for a computer clock signal. The majority of the time is spent constructing and troubleshooting a simple model for a traffic light controller, consisting of a 1 Hz oscillator, a two-bit counter, and a binary decoder to produce a four-state machine. Red, yellow and green LEDs are connected to appropriate outputs so that the LEDs flash in the sequence produced by a two-way traffic signal. This project provides a way to connect the abstract ideas of digital circuits and multi-state systems with an example from everyday life.

The project has been conducted on an annual basis for over ten years. Key to the success of this activity is the support provided by faculty and students in the ECE department. Undergraduate and graduate students assist in construction and troubleshooting of the circuits, with at least one ECE student for each two participants. The participants benefit from the exposure to the technical content as well as the social interaction with the ECE students. The ECE students also benefit, reinforcing their own mastery of circuit construction and testing by explaining it to others. Participants complete surveys indicating what they learned from and enjoyed about the program, and responses support that this exercise is both interesting and useful, with over 75% reporting that they learned a lot and over 90% recommending that it be continued.

2. Introduction

Increasing ethnic diversity has been a goal in undergraduate engineering programs for decades, and yet the percentages of women and underrepresented minorities in many engineering programs continues to be below the percentages of these groups in the general population [1], with 5% or fewer of bachelor's degrees awarded to African American students, fewer than 10% of bachelor's degrees awarded to Hispanic students, and fewer than 20% of bachelor's degrees awarded to women, for the years 2006-2014 [2]. The statistics for ethnic diversity are similar for Electrical Engineering and Computer Engineering (and joint EE/CoE) programs, with 5.4% of bachelor's degrees awarded to African American students and 10.3% of bachelor's degrees awarded to Hispanic students, while the statistics for gender diversity are even more skewed, with only 12.4% of bachelor's degrees awarded to women, for the academic year 2013-14 [3]. The Swanson School of Engineering at the University of Pittsburgh actively promotes a diverse population of undergraduate and graduate students, faculty and staff through measures that are aligned with widely cited studies of the best approaches to improving ethnic diversity in engineering programs [1,4].

The Engineering Office of Diversity provides a comprehensive pipeline of programming from pre-college through graduate school that supports academic excellence. Our pre-college diversity program, INVESTING NOW, works with high achieving high school students, primarily from groups historically underrepresented in science, technology, engineering and mathematics (STEM), and prepares them for majors in STEM fields. The undergraduate diversity program supports the recruitment, retention and graduation of academically excellent engineering undergraduates. The Engineering Office of Diversity also sponsors recruitment and retention initiatives to support graduate education, implements diversity training for faculty, students and staff, and assists with faculty recruitment.

Students in the pre-college program are involved in academic advising, tutoring, career awareness and college planning seminars, and hands-on science and engineering experiences. Additionally, students in the ninth through the eleventh grade attend a summer enrichment program on the University campus. They attend non-credit classes in mathematics, science and writing in the morning and participate in an engineering project class in the afternoon. In past years, ninth grade students have participated in a robotics project, tenth graders have participated in a bioengineering project and eleventh graders have participated in an alternative energy and sustainability project. Annually, approximately 175 students participate in this year-round program.

In order to enhance interest and knowledge in STEM fields, students in the pre-college program participate in the Hands-On Science and Engineering (HOS&E) component. The goals of this component are to:

- Provide hands–on experiences in science and engineering.
- Provide opportunities for students to interact with science and engineering professionals, as well as graduate and undergraduate students.
- Show the linkage between high school math / science classes and science or engineering–related fields.
- Show students that careers in science and engineering are within their reach.
- Encourage students to choose science or engineering majors in college.

HOS&E activities are facilitated by a variety of University science and engineering departments, schools, and professional organizations. Typically, the students are required to participate in three to four HOS&E activities per year during the ninth, tenth and eleventh grade. Sessions are interactive, allowing students to learn by experience. Table 1 lists the departments, schools and organizations that offered HOS&E activities to students in the pre-college program in 2015.

Ninth Grade	**Tenth Grade**	**Eleventh Grade**
Biological Sciences	Physics	Dentistry
Chemistry	Scientists, Engineers and Mathematicians for Services (SEMFS) – a student organization	Electrical and Computer Engineering
Nursing	School of Health and Rehabilitation Sciences	Medicine

Table 1: Departments hosting Hands-On Science and Engineering Activities (2015)

The remainder of this paper discusses the activity conducted by the Electrical and Computer Engineering department for eleventh-grade students. In this three-hour project, participants construct a digital logic circuit that models a traffic signal, consisting of an oscillator, a two-bit counter and a binary decoder. University students assist the participants with the construction, testing and troubleshooting of the circuit, and introduce them to what it is like to be in an undergraduate laboratory course. The joint goals are to impart a limited amount of technical information and experience with prototyping, and for the participants to gain confidence in their ability to complete tasks like those they would see if they were enrolled in the ECE program at an the University of Pittsburgh.

A variety of different approaches to introducing pre-college students to engineering concepts have appeared in the literature, including some that use robotics competitions [8,9] as the basis for the project, another that exposes high school teachers to fuel cell technology [12], and others that introduce students to industrial co-operative education experiences in medical imaging, IC design and mobile radio [13], or to academic research [11]. Our activity differs from those listed above, in that it is focused on low-level circuit prototyping, it relies on interaction between participants and current undergraduate students to complete the project, it is completed in a single three-hour session, and because it is only one of nine activities in different fields that are part of the INVESTING NOW program. The activity we have found in the open literature that is most similar to ours [10] involves teaching microcontroller prototyping and programming to K-12 students. That program goes well beyond what we describe here, because it involves much more technical content delivered over many four-hour sessions, and because it involves a course for undergraduate students, wherein they learn the skills necessary to teach the K-12 participants.

3. Project Description

This project is completed in one three-hour session that is normally conducted on a Saturday morning in one of the undergraduate circuit prototyping laboratories. Following a welcome message and introduction of the participants, the activity begins with a brief overview of fundamental concepts in digital circuits: voltage and current, Ohm's law, the circuit model for a flashlight, base-two arithmetic, and binary representations of numbers and data. This is presented in a typical lecture format and lasts only a few minutes.

The next goal is to have the participants briefly use an oscilloscope to observe and measure the calibration signal, which is a 1.2 kHz square wave that is produced by the oscilloscope itself. The participants are instructed in how to connect the signal to the oscilloscope input, and once they have the signal displayed, how to measure the voltage levels relative to ground and the period of the waveform. This section concludes by describing how this kind of signal is used as the system clock in computers and other digital circuits. Typically, work with the oscilloscope is finished about fifteen minutes after the participants arrive in the lab.

3.1 Square-Wave Oscillator

Most of the session is devoted to the construction, troubleshooting and testing of a simple digital circuit that is a model of a traffic-light controller. The first major component of this circuit is a square-wave oscillator circuit, constructed using the LM555 timer IC in an astable configuration [5]. The signal so produced will be used later as the clock signal for the other components. The resistor and capacitor values are chosen to set the period of the output at approximately 1 Hz, and the IC and other components are provided to the participants by the University students at the times they are needed.

This portion begins by distributing plug-in prototype circuit boards to the participants, and showing them how the boards are used to make circuit connections and how to connect their circuits to the power supply. The students are provided with LEDs, they learn how to find the anode and cathode, and the LEDs are used to test the power connections on the protoboard.

The oscillator circuit is constructed in stages: placing the IC in the protoboard, making wire connections, connecting capacitors, connecting resistors, and finally connecting an LED to the output to test the circuit functionality. Each step is described by a slide that explains what to do in a few bullet points, along with an image of the circuit after that step has been completed. We have found that this use of photographs makes the project accessible to high-school students, without having to teach them the meaning of symbols in schematic diagrams. An example slide is shown in Figure 1, in which all connections for the oscillator have been made, with the exception of the LED to monitor the circuit output.

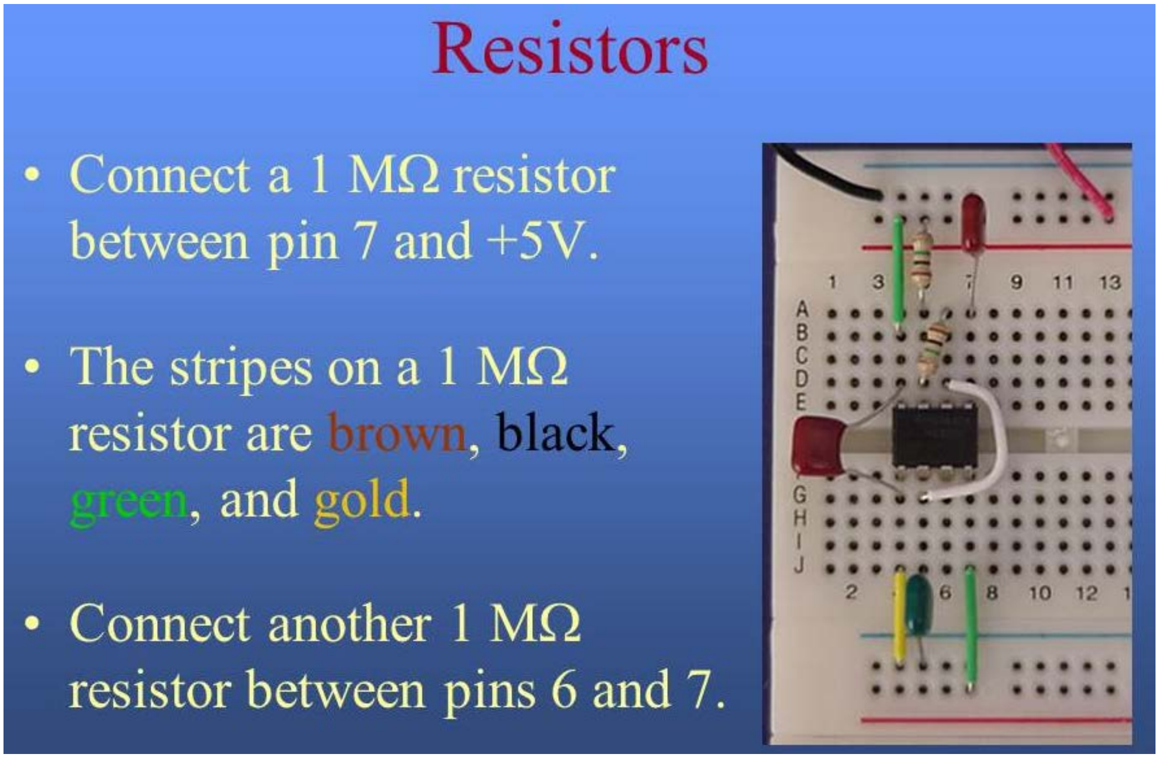

Figure 1: Example Slide, LM 555 Square-Wave Oscillator

The slides that describe the project are displayed on a projector, and each step is described in a lecture format before proceeding. The entire slide show is also available locally at each participant's workstation to allow everyone to proceed at their own pace. Throughout this process, the participants are assisted by University students, who explain any steps that are unclear, demonstrate how to make proper connections, and assist with circuit testing and troubleshooting.

It is extremely common for some participants to have difficulty getting the oscillator working properly, either because of wiring errors or problems with the hardware or protoboards, while others plug the components in and have it work immediately. We will sometimes devote two or more University students work with a single circuit that is proving to be especially troublesome, with the goal of getting all students to complete the oscillator by roughly the one-hour mark.

These kinds of difficulties with the circuits are an important part of the learning experience, and the methods employed to solve them instigate social interaction among the participants and between the participants and University students.

3.2 Two-Bit Counter

The second major component of the project consist of a 7474 D-flip-flop, configured as a two-bit ripple counter [6]. A brief lecture is provided to review counting in binary, and the output sequence produced by the counter. Construction is again completed in stages: connections to power and ground, construction of the least significant bit, connection to the oscillator output, testing of the least-significant bit, and construction and testing of the most significant bit. An example slide from this section is shown in Figure 2, which depicts the completed counter with all connections for both outputs.

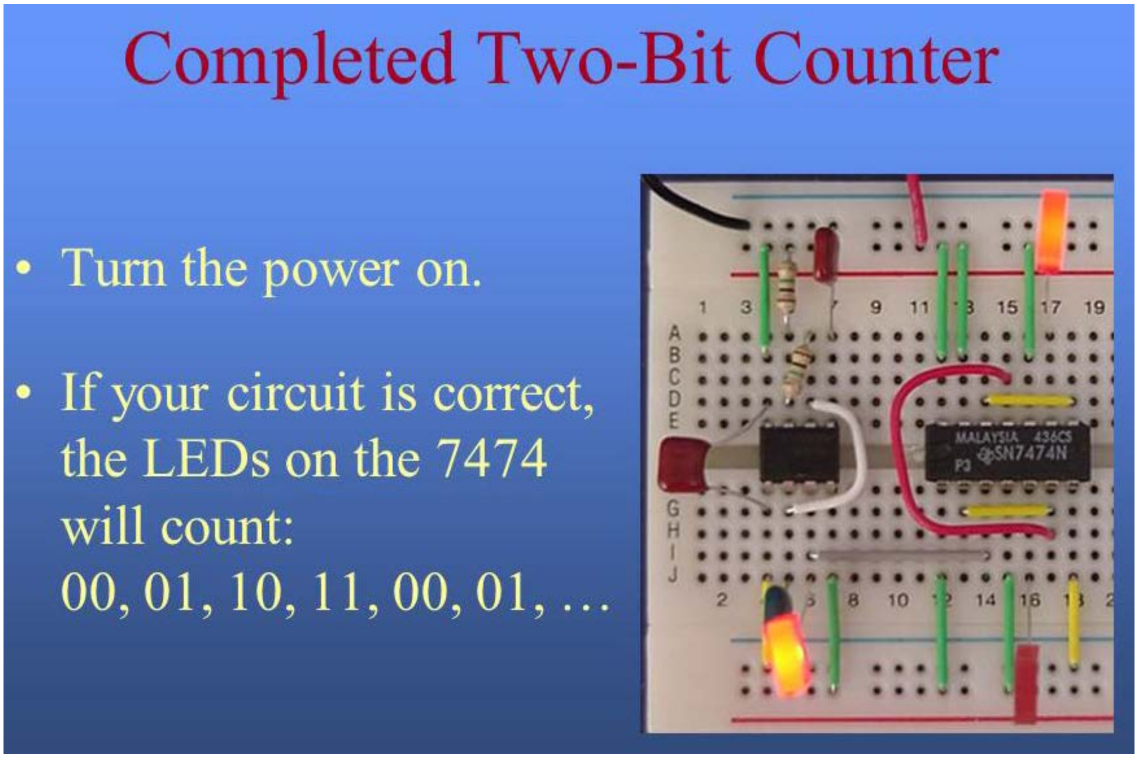

Figure 2: Example Slide, 7474 D Flip-Flop Wired as a Two-Bit Ripple Counter

Participants also encounter problems with the two-bit counter, resulting from wiring errors, problems with the 7474 chip or protoboard, or the LED connected to the oscillator output pulling the high output voltage down, such that it is unable to trigger the counter. This provides an enhanced troubleshooting experience for the participants, because each flip-flop on the 7474 can be tested in isolation, whereas the oscillator can only be tested in its entirety. It also serves as a learning experience for the University students, who deepen their understanding of the logic circuits by having to explain their function to the participants.

There is very little lecturing during this portion of the project. The instructor will interrupt the group a few times to give an overview of the counter and how it is constructed, but otherwise everyone works on construction and troubleshooting the circuits. The various participants are often progressing at widely varying rates at this point of the project, and the University students adapt their assistance to maximize the progress of the group as a whole. The goal is to have the counter circuits working after 90 minutes have elapsed, and it is important to ensure that no one gets discouraged by falling far behind the others.

3.3 One-Hot Counter

The third major component of the circuit is a 74139 binary decoder. When the outputs from the two-bit counter are connected to the select inputs of the 74139, the result is a one-hot counter with four outputs [7]. Perhaps a more apt name in this case would be a "one-cold" counter, because the outputs of the 74139 are active-low, and so for testing purposes the participants connect LEDs between the decoder outputs and the +5V power supply rail. For any combination of outputs from the two-bit counter, exactly one of the decoder outputs is set low, and then corresponding LED is illuminated. Figure 3 shows the slide from the end of the section on the one-hot counter, with all connections completed.

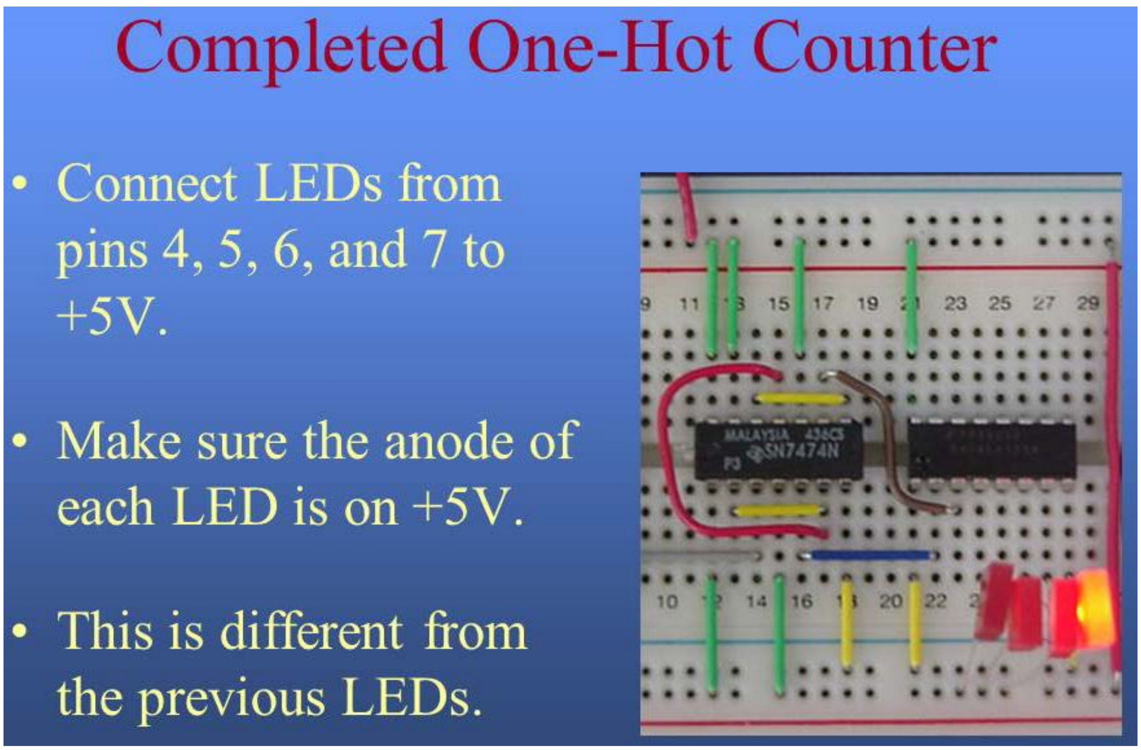

Figure 3: Example Slide, 74139 Binary Decoder Wired as a One-Hot Counter

Figure 3 also shows the 7474 D-flip-flop, from which the LEDs previously used for testing have been removed. This is usually necessary in order for the outputs from the 7474 to have sufficiently high output voltages to drive the inputs to the 74139. This is the most common troubleshooting issue with the one-hot counter, followed by errors in wiring the testing LEDs and the occasional 74139 whose outputs cannot sink enough current to illuminate the LEDs without current-limiting resistors. These issues, and that of the active-low outputs, provide an additional challenge for the participants to understand the circuits, and lead to opportunities for additional interaction with the University students who try to explain these ideas. The goal is to have this portion of the project completed after two hours have elapsed.

3.4 Traffic Light Controller Model

The final circuit uses the outputs of the two-bit counter and the one-hot counter to model the sequence of lights for a simplified traffic signal at an intersection:

Red/Green, Red/Yellow, Green/Red, Yellow/Red (Repeat).

This section of the project begins with a brief lecture to explain the relationship between the states of the counter they have constructed and the states of the traffic signal. The abstract notion of a state in a sequential logic circuit is something that undergraduate engineering students have difficulty understanding at first, and the intent here is to connect this idea to something all students experience every day. Figure 4 is a slide taken from this portion of the project to explain the function of the controller circuit.

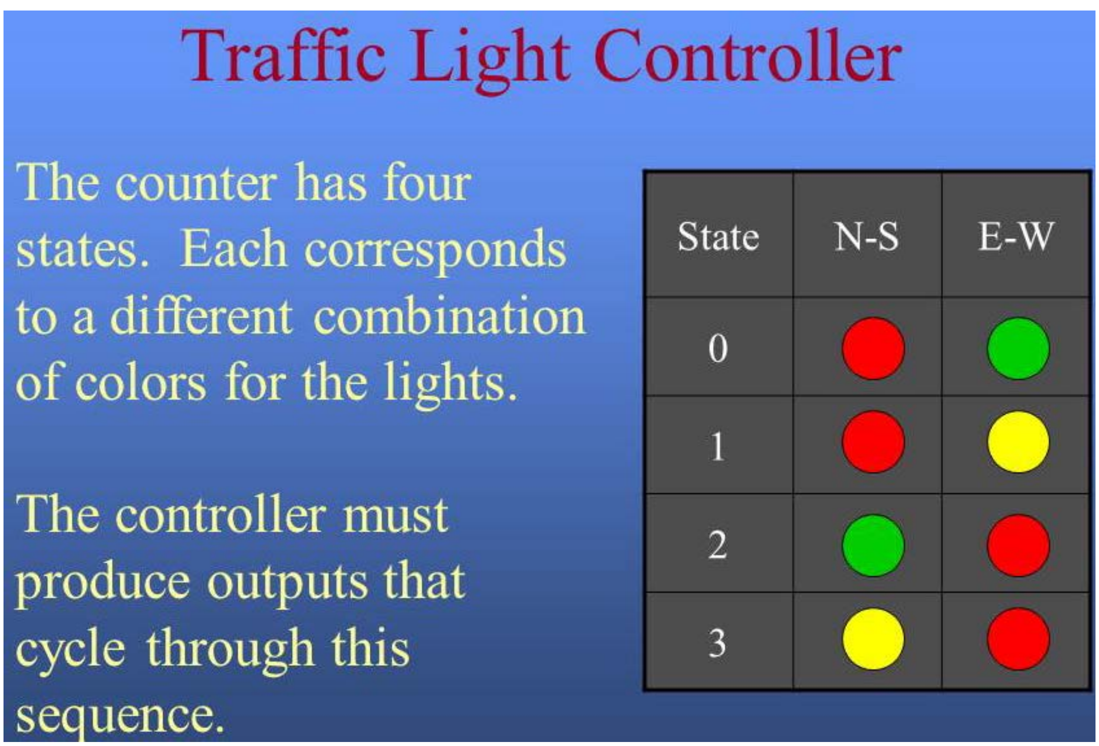

Figure 4: Example Slide, States of the Traffic Light Controller

The only modifications to the circuit at this point are to connect red, yellow and green LEDs so that they flash in the proper sequence. The Q and $\overline{Q}$ outputs from the most-significant bit of the two-bit counter are used to drive the red LEDs, which must be illuminated for two consecutive clock cycles each. The outputs from the one-hot counter are used to illuminate the yellow and green LEDs, which are each illuminated for one clock cycle out of four. All six LEDs are connected between the appropriate output and the +5V power rail, so that each LED is illuminated when the corresponding output goes low. In addition, 100Ω current-limiting resistors are placed in series with the red LEDs, so that when the counter output pins are set high, the voltage remains high enough to drive the select inputs of the 74139 decoder.

This portion of the project requires the least amount of circuit construction, but it can often lead to the greatest amount of time and effort spent in troubleshooting, because of the number of different connections to LEDs, the requirement that the flip-flop outputs drive both LEDs and the select inputs of the decoder, and our inability to capture all of the interconnections accurately through photographs. Nevertheless, the participants are highly motivated to complete this step and see the completed circuit in action, and in most cases have gained significant confidence in their ability to construct the circuit based on their success in completing the earlier steps. Figure 5 shows a slide from the end of the project, including an image of the completed circuit. Note that it is very difficult to tell in the image precisely where each LED is connected, but the slide show contains images from other perspectives to help in this regard.

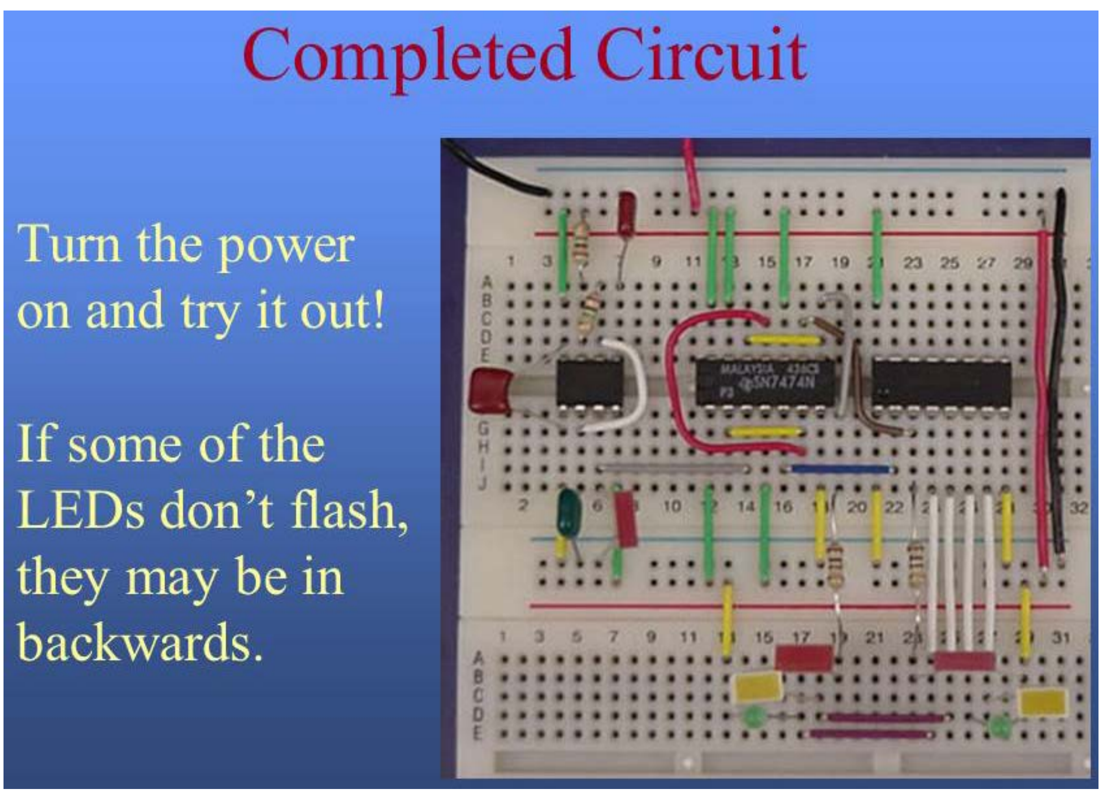

Figure 5: Example Slide, Completed Circuit

Our goal is to have all participants construct a complete working circuit by the end of the three-hour session, with perhaps 15 minutes at the end for concluding remarks, social interaction and cleaning up. In the first few years of conducting this activity, relatively few participants were able to finish the circuit, largely because of circuit troubleshooting issues that took a long time to solve. Since then, our group has collectively learned where many of the common stumbling blocks occur, such that the University students can anticipate these problems and suggest solutions in a timely manner. As a result, in recent offerings it is common for all participants to complete the circuit before the end of the activity. Many University students participate in the activity for several years, with the result that the knowledge about troubleshooting issues is passed down to newer students.

4. Participant Feedback and Assessment

Participants in the Hands-On Science activities complete surveys regarding the quality of the activity, what they learned, and whether they recommend providing the activity to future participants. Results from four multiple-choice questions from these surveys are presented in Figures 6-9. The questions to which the participants responded are:

- The overall content of today's program was (Excellent, Very Good, Good, Fair, Poor)
- The use of hands-on activities was (Excellent, Very Good, Good, Fair, Poor)
- Today I learned _______ new information (A lot of, Some, Very Little, No)
- Should we offer this program again next year? (Yes, No, Unsure)

The survey results cover a sampling of activities conducted over an eleven-year period; data are not available for years not shown in the figures, but the activity was conducted at least once per year from 2003-2016. Throughout this time the circuit project and supporting materials remained the same, although the delivery improved with repetition and experience. The number of participants for each data for which we present data is provided in Table 2.

Date	Oct 2004	Oct 2005	Feb 2006	Feb 2009	Apr 2010	Mar 2014
Participants	16	16	14	18	11	14

Table 2: Number of Participants in each HOS&E Session

Figures 6 and 7 demonstrate that the participants generally find the activity to be a useful experience, with more than 90% reporting that the content and use of hands-on activities was very good or excellent. Three surveys indicated that less than 90% of participants found the content very good or excellent (Oct-05: 81%, Feb-06: 86% and Feb-09: 89%) and one survey indicated that less than 90% thought the hands-on activities were very good or excellent (Feb-09: 89%).

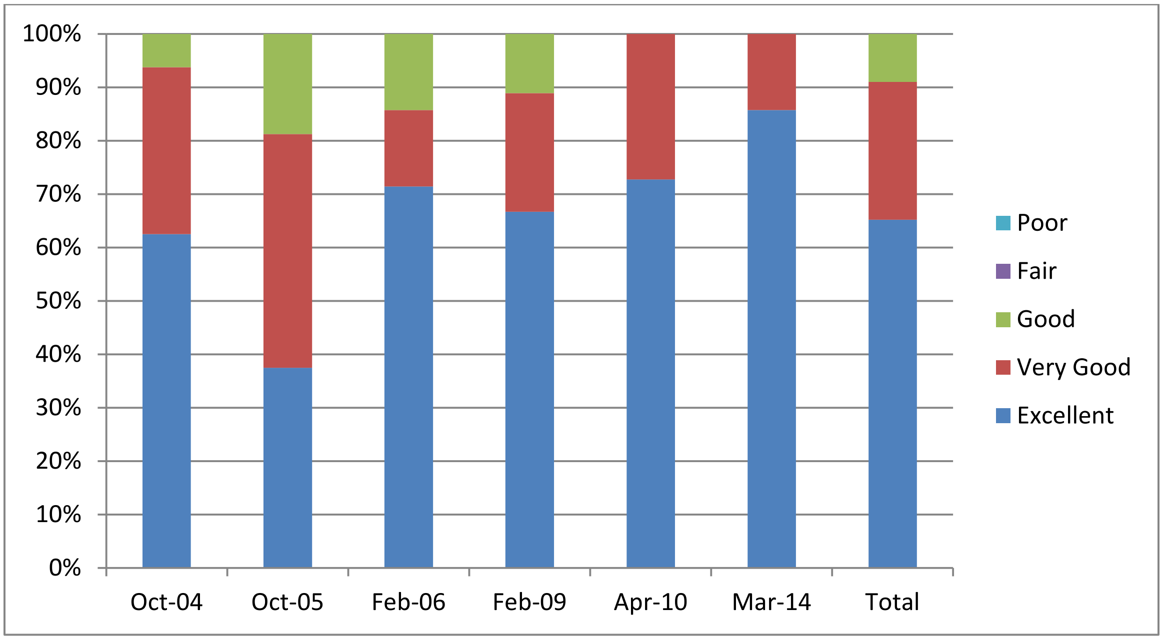

Figure 6: Survey Results, “The overall content of today’s program was”

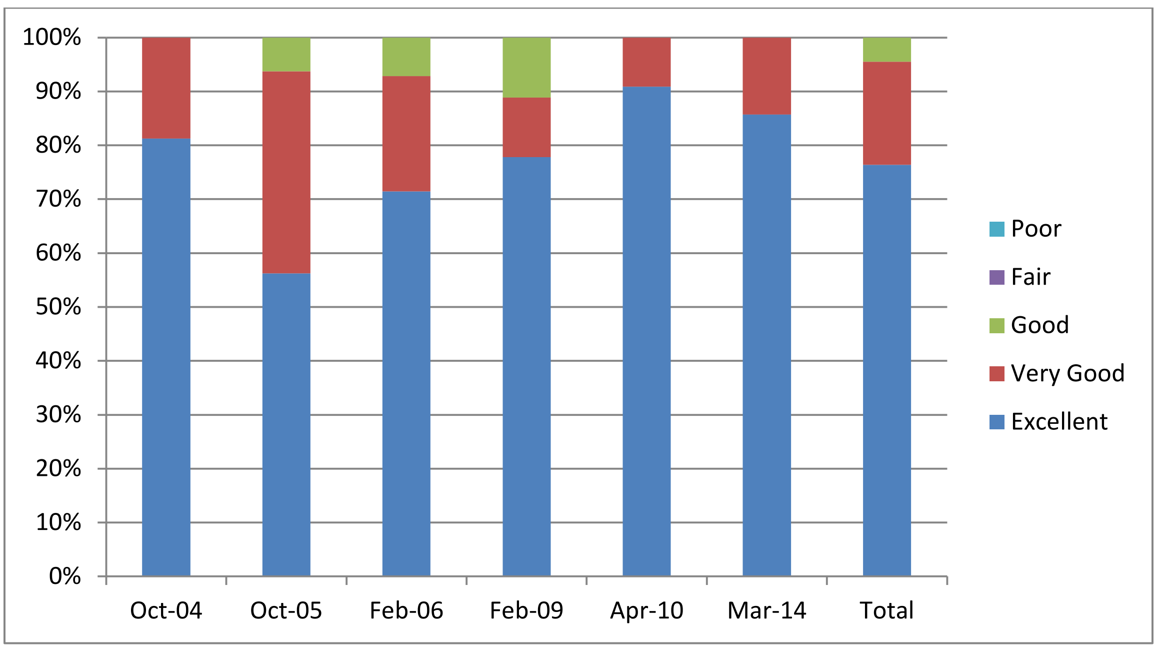

Figure 7: Survey Results, “The use of hands-on activities was”

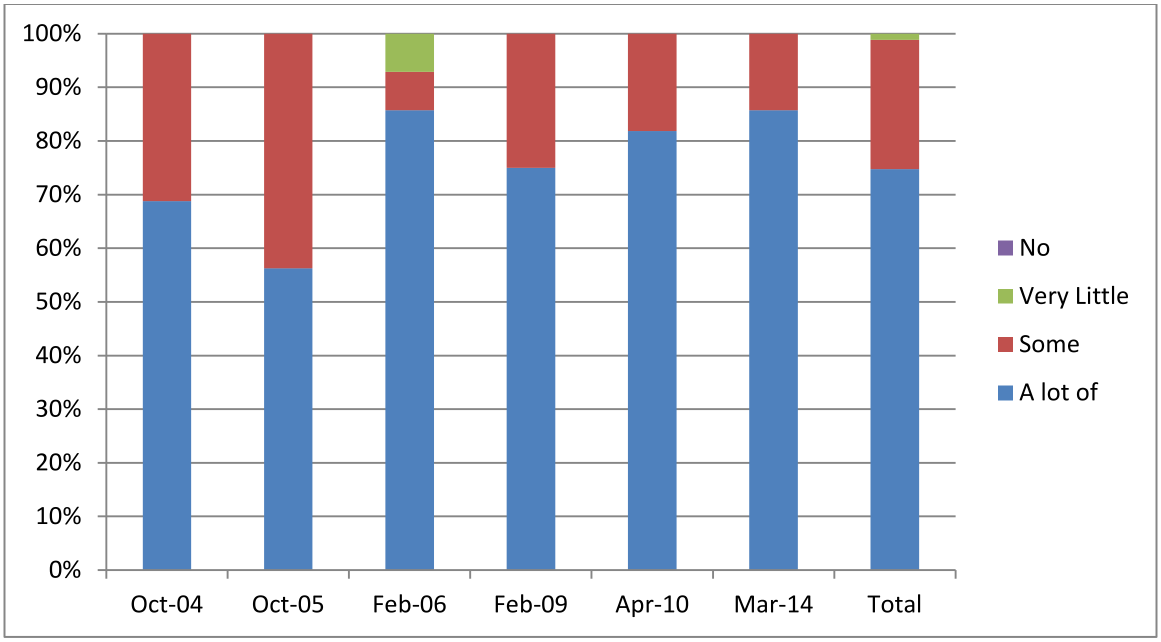

Figure 8: Survey Results, “Today I learned _______ new information”

There is also a general trend of increasing satisfaction over time, and this result is consistent with the overall performance of the participants in completing the project, as reported in Section 3.4.

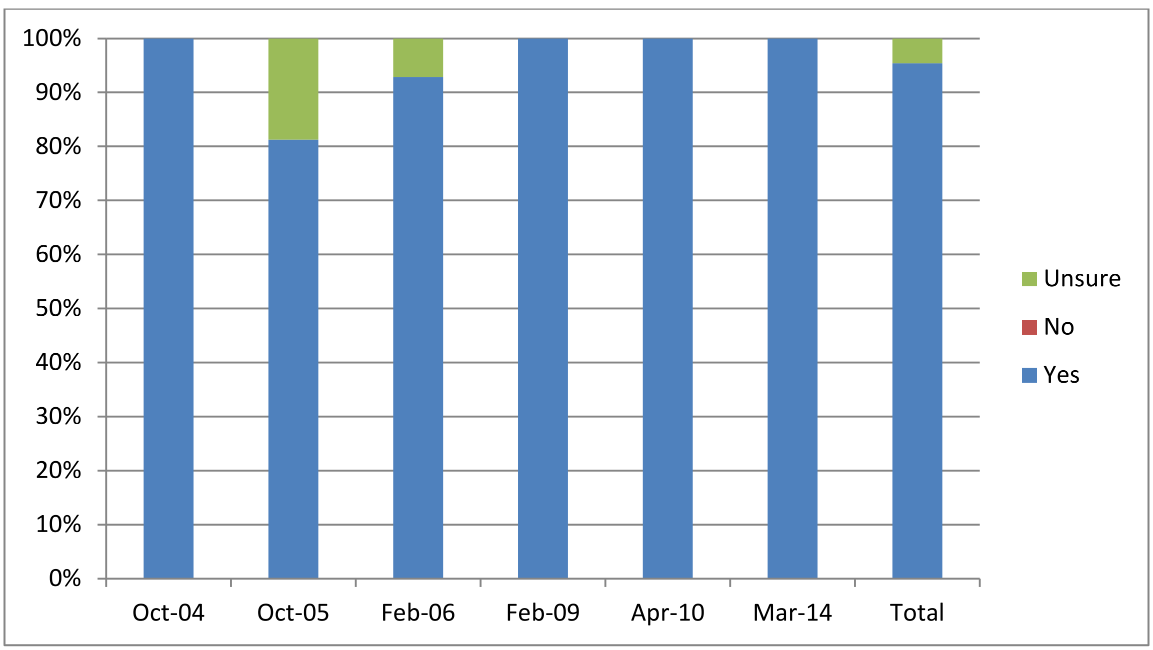

Figure 9: Survey Results, “Should we offer this program again next year?”

Figures 8 and 9 further support that the participants have a positive impression of the activity, with over 75% indicating that they learned a lot, and over 90% indicating that it should be offered to other participants in the future. Two groups reported that less than 75% of participants learned a lot (Oct-04: 69% and Oct-05: 56%) and one group reported that less than 90% would offer the program again

(Oct-05: 81%). These results also indicate a general trend of improving satisfaction over time, but unfortunately the data that are missing between 2010 and 2014 prevent us from making a stronger statement.

The surveys also include three open-ended questions about what was learned during the activity, the best part of the activity, and what should be improved. Responses to the question “List two things you learned today,” can be summarized as follows:

- The majority of responses (67/111, 60%) listed specific technical information contained in the project, such as how to wire a circuit on a breadboard, the cathode and anode of LEDs, and what a two-bit counter is.
- A significant minority of responses (42/111, 38%) listed general content that was part of the project, such as how to make a traffic light simulator, and what computer engineering is.

Responses to the question “List the part(s) of today’s program you enjoyed most,” were more varied, but many fell into two general categories:

- Nearly half of the responses (37/75, 49%) included some element of the overall experience that was enjoyable, such as learning something new, interacting with the University students, and the satisfaction of getting the circuit to function correctly.
- A large portion of responses (30/75, 40%) included specific portions of the project that were enjoyable, such as learning how to wire circuits or learning about how computers work.

There were relatively fewer responses to the question “List two ways to improve today’s program.”

- A majority of the responses (40/67, 60%) indicated that no improvements were necessary.
- Some of the participants (11/67, 16%) indicated that they would have appreciated having more time to work on the project, or the opportunity to take the completed circuit home.
- Some of the participants (10/67, 15%) wanted to learn more about the circuits and how they function. Unfortunately, it is not possible to teach high-school students about the details of logic circuits in one day.

Overall, we find the responses to the open-ended questions to be particularly encouraging, because they show that the students are engaged by the activity, learn at least the basic skills that we hope to impart to them, and leave the session wanting to know more about logic circuits and engineering.

The class of 2015 was the twenty-second student cohort to participate in the pre-college program, including the HOS&E activities. (Recall that the ECE activity described here is only one of nine activities offered to students in grades 9-11). Significant statistics for this group include:

- 100% enrolled in college
- 71% chose an engineering, mathematics or science major
- 39% enrolled in engineering as a major
- 13% enrolled in the Swanson School of Engineering

Statistics showing enrollment in college and STEM majors for the past seven years of the pre-college participants are shown in Figure 10.

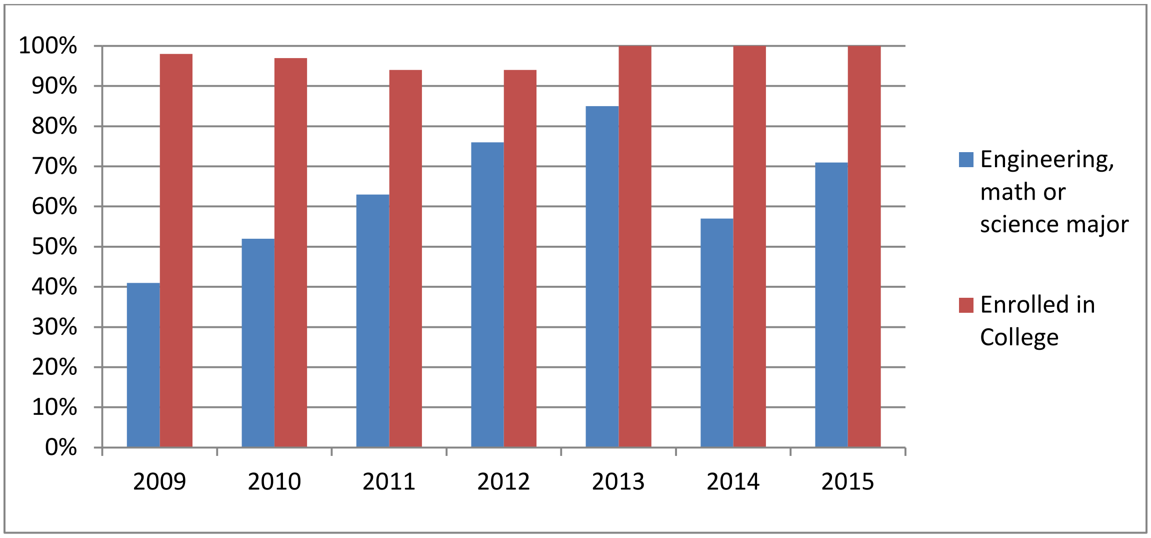

Figure 10: Enrollment and STEM Major Statistics for Pre-College Participants

These results are very encouraging for the success of the pre-college program as a whole, especially because 100% of the participants enrolled in college for the last three years, and the majority have consistently pursued STEM majors. These are two of the primary goals of the program. Note that we do not have data indicating how many students ended up specifically in engineering or ECE programs, but we do not consider these to be specific goals of our efforts. Although our activity focuses on digital logic circuits, it is important to remember that it is part of a much broader set of Hands-On Science and Engineering activities, which are in turn part of the larger set of elements in the pre-college program. We hope that the experience of this activity will leave the participants with the confidence that they could pursue Electrical or Computer Engineering if they choose to, but there are many factors driving a student's choice of major, and it would be unreasonable to expect that a single Saturday morning project would have a strong influence on this decision.

5. Conclusions.

The activity described here provides high school students with exposure to basic information about digital circuits, experience with construction, testing and troubleshooting, and interaction with University students who are enrolled in an undergraduate program in Electrical or Computer Engineering. Goals for the participants are imparting some technical knowledge, gaining confidence in their ability to pursue a STEM major, and social interaction with the University students and our survey results indicate that these goals are largely being met.

Improvements to our approach to assisting the participants over time has produced an activity in which nearly all participants are able to complete construction of a complicated logic circuit in a single three-hour session, something far beyond what most would have expected of themselves prior to the activity.

Although this project represents only a small part of a larger effort to increase ethnic diversity in engineering programs at our University and other schools, we plan to continue to offer the program and improve it over time. A second HOS&E activity hosted by the ECE department has been developed (by a colleague who is not an author on this publication), in which the participants develop code for a microcontroller and a smart phone to monitor the status of a temperature sensor. In addition, we have twice offered an alternate version of the traffic-light project with middle-school students, in which the activity is conducted in their classroom over five 30-minute sessions.

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