Build to Win: Electrical Hardware Opportunities for STEM Education

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Abstract - **Engineering outreach and introductory courses are essential for motivating and training the next generation of capable engineers. Accessibility and portability of the infrastructure for a STEM course is critical for spreading STEM education and motivation efforts. The ubiquity of student personal computers and laptops provides a convenient platform for introducing computer programming, but the relatively cumbersome equipment deemed necessary for a hands-on electronics learning environment contributes to the lack of electronic circuit hardware exposure for many K-12 students and university undergraduates. This paper presents the relatively low-cost, versatile, electronics platform we have developed at MIT upon which our new, hands-on introductory STEM electrical engineering course has been built and taught in recent years. This paper focuses its discussion on the power supply and measurement systems we have produced that allow students and instructors to engage in hands-on electric circuit exercises and projects without the requirement for expensive laboratory infrastructure. Example demonstrations of introductory laboratory exercises using our platform are shown.**

Index Terms - Electronics, Hands-on learning, Engineering curricula, Engineering outreach, STEM education.

INTRODUCTION

Incoming engineering undergraduates are much more likely to have spent their time "surfing the web" than "working on the Ford." The increasing complexity and monolithic integration associated with modern commercial products have conspired to eliminate many of the practical, hands-on experiences that prepared past students for an engineering education. At the same time, many of our classes have been refined to focus on the beauty and technique of analytical methods and fundamental principles used in design, perhaps increasingly without reference to the practical physical systems for which these methods were developed. These trends may account for our informal observation that many engineering students appear less aware of the practical magic made possible by physics and electrical engineering (EE). A balanced educational experience, which combines a good appreciation of exciting, contemporary analytical techniques and computing tools with the essential ability to manipulate and understand the physical world, will enable a student to combine new tools with classical methods to design real systems.

These concerns may seem at odds with opportunities provided by readily available STEM activities. A substantial "ecosystem" of electronics projects and project components, generally oriented around systems like the Arduino [1] or Raspberry Pi [2] for example, offer lots of opportunities to play with sensors, wiring, small actuators, and optical components like light emitting diodes (LEDs) and small camera integrated circuits (ICs). These modules are pre-packaged in the sense that they fit together like "LEGO" blocks. They obstruct students from connecting physics and design calculations with function, relegating most of the "project work" to developing code to patch pre-packaged hardware subsystems together. A more balanced introduction allows students to view physics and engineering principles as a pallet of limitlessly combinable and designable functions that can create complex and creative systems. Genuinely educational experiences, as opposed to basic training, lead students to create content rather than consume it as preconceived blocks designed elsewhere.

Hands-on laboratory exercises and project-based learning (PBL) are critical for providing both K-12 and undergraduate university students with a fulfilling STEM education experience. Project-based courses, with emphasis on creativity [3] or student reflection [4], have a positive effect on engineering student experience. PBL can also provide students with practical skills valued by fast-moving industry [5]. STEM outreach programs, such as For Inspiration and Recognition of Science and Technology (FIRST), have been very successful in exposing K-12 students to exciting STEM exercises and inspiring careers in STEM [6]. Traditional outreach programs or platforms, however, often focus specifically on mechanical or programming challenges, where the underlying electrical circuit hardware of a complete project is not explored. In a recent review of robotics-based STEM education research, computer programming was by far the dominant focus, covered by 25 of 36 robotics-based STEM education studies published between 2012 and 2021 [7]. These are excellent strides for STEM education as a whole, but motivational educational outreach opportunities for electrical hardware and circuits are more limited than programming opportunities.

Electronic circuit topics elegantly integrate mathematics and electromagnetic physics lessons with practical engineering and building exercises. The costly barrier of the equipment for powering and debugging electronic systems, however, hinders the opportunity for students to experience lucrative and motivating creative building exercises. Fortunate university EE laboratories are often equipped with prohibitively expensive test equipment, such as lab bench power supplies and high-performance oscilloscopes. Such relatively expensive equipment is valuable and necessary for advanced undergraduates and graduate students in EE programs. Other approaches are necessary to expand access for a K-12 or first-year undergraduate student to begin to explore the world of electronic hardware at an introductory level in a hands-on way. Many institutions, particularly K-12 education centers, cannot be expected to have the physical space or funding to maintain university-style EE laboratories.

We have recently deployed a hands-on introductory electronics course at MIT to test new approaches for engaging students with electronics design. This course is referred to as Electronics FIRST (MIT course number 6.2030). Electronics FIRST includes 12 laboratory exercises in which students solder and assemble a printed circuit board (PCB) for each exercise as they learn the circuit theory underlying each PCB's performance. This paper briefly introduces the pedagogical approach to the Electronics FIRST laboratory exercises, and then focuses its discussion and demonstration toward foundational components for hands-on circuits building: a power supply and a measurement module.

HANDS-ON DESIGN OPPORTUNITIES

Specifically, we have developed a modular electronics system that promotes opportunities for students to build key functional circuits using design choices informed by physics calculations. The modular functional blocks that students build are designed to be "fun." In other words, each PCB block provides some (hopefully) exciting output to a user by glowing, flashing, producing a musical tone, etc. Each functional block introduces an electrical engineering concept, with exercises ranging from Ohm's Law and divider circuits to oscillators, resonance, and embedded programming. The blocks require design calculations for the intended function to succeed. They facilitate both "training" for skills like soldering and measurement, and also "education" for flexible opportunities in functional design. The system's small modular PCBs can be interconnected and eventually used to create even more complex and interesting projects. Figure I shows a suite of several of the Electronics FIRST PCBs that students build throughout a semester

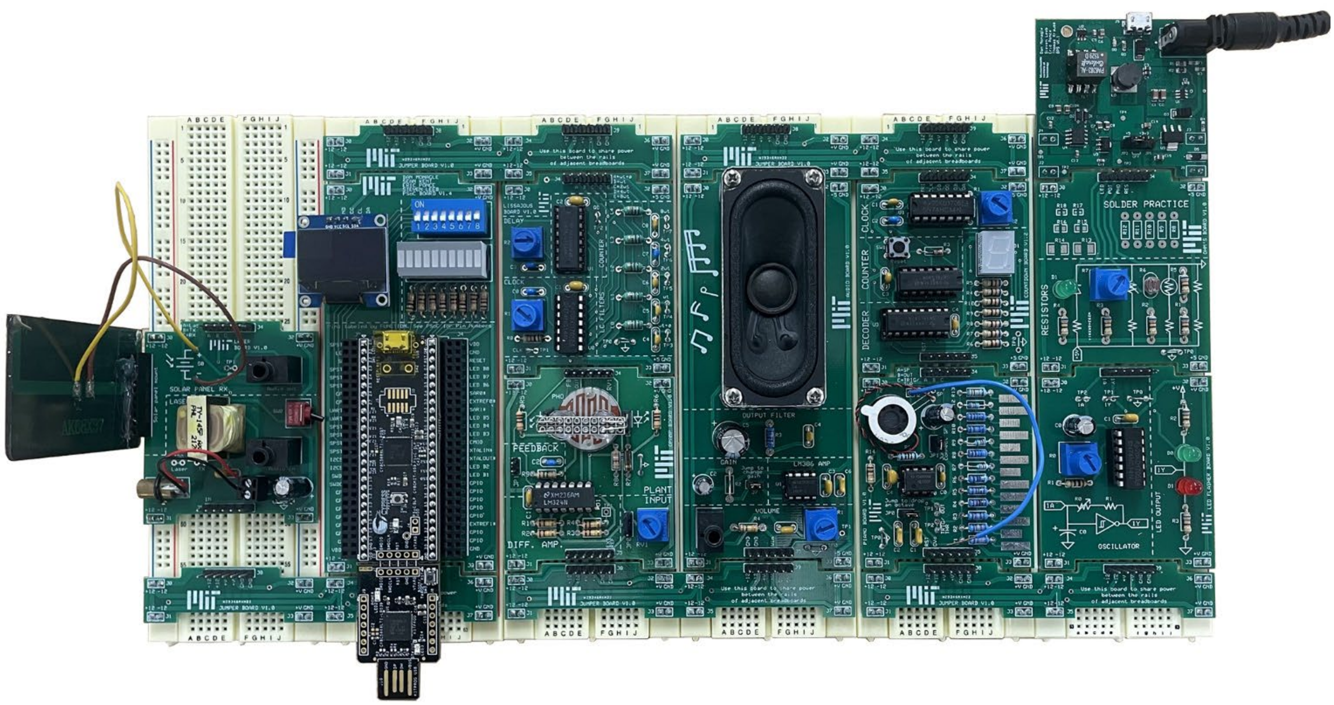

FIGURE I

A SUITE OF ELECTRONICS FIRST LAB EXERCISES. THE LABS INVOLVE MODULAR PCB BUILD SESSIONS, AND BOARDS CAN BE COMBINED TOGETHER FOR CREATIVE PROJECT USE.

Students are issued a new, unassembled PCB along with a laboratory exercise handout on an approximately weekly basis. Working with our teaching team and lecturers, students learn an important theoretical concept that is illustrated by each PCB they build. These concepts become building blocks that students can use to design and assemble more complex systems during a final project. Each PCB in Electronics FIRST is shaped such that its outline exhibits a protruding tab with test points at the "top" of the board and an indented tab at the "bottom" of the PCB. This mechanical outline acts as a standardized keying system, helping to ensure the laboratory PCBs are installed with proper power supply connections during building.

To enable the widespread outreach of electrical hardware opportunities in STEM education, a versatile, reasonable-cost, and portable means of powering and debugging the project circuitry is required. Here, we describe a power supply and measurement platform we have designed and fabricated at MIT with the hope of equipping educators with a more practical and accessible infrastructure for exposing students to hands-on exercises with electrical circuits. The primary goal of the versatile power and measurement system described in this paper, beyond directly supporting laboratory exercises in Electronics FIRST, is to act as a relatively low-cost and simple substitute to traditionally costly and bulky benchtop power supplies and oscilloscopes.

SUPPORT HARDWARE

Our hardware platform for enabling hands-on electronics opportunities consists of three key modules:

- Breadboard Power Supply (BPS)
- Power Rail "Jumper Board"
- Programmable System-on-Chip (PSoC) Oscilloscope

These easy-to-use low-cost modules provide widespread accessibility for EE education. The following subsections describe each module in detail.

I. Breadboard Power Supply (BPS)

A photograph of the BPS is shown in Figure II.

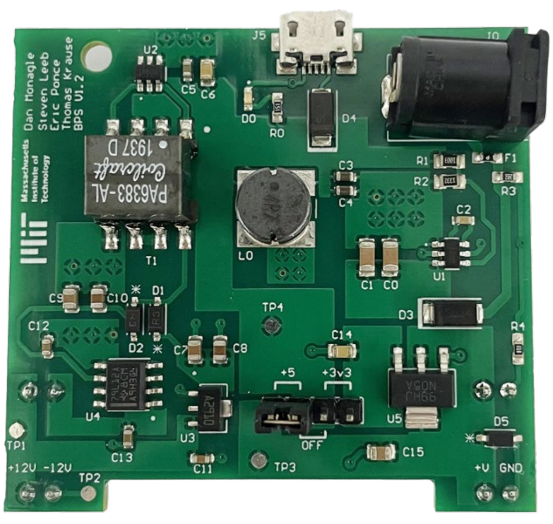

FIGURE II

THE BPS POWER RAIL +12V, -12V, +5/3.3V, AND GND PINS COMFORTABLY PLUG INTO THE VERTICAL RAILS OF A STANDARD SOLDERLESS ELECTRONICS BREADBOARD.

The BPS is a pre-assembled PCB intended to be issued to students and instructors as the power supply for all laboratory exercises in Electronics FIRST, including student-driven final projects. The BPS plugs directly into a standard solderless electronics breadboard and accepts either a Type-B Micro-USB input or a barrel jack connector. An indicator LED illuminates when input power has been provided to the BPS. The BPS provides 4 regulated output power rails, +12V, -12V, a user-selectable +5/3.3V, and 0V, to the 4 vertical power rails included on a standard solderless breadboard. A two-pin jumper is used to select between +5V or +3.3V operation. A distinguishing feature of our BPS compared to commercially-available breadboard power supply modules are the +12V and -12V rails, which are often not included on the commercial modules despite being very useful for powering introductory analog circuitry, such as operational amplifier circuits. The output power specifications of the BPS are recorded in Table I.

TABLE I

BPS OUTPUT POWER SPECIFICATIONS

Output Voltage Rail	Maximum Output Current Specification
+12V	200mA
-12V	100mA
+5V (Micro-USB input)	Maximum current output of Micro-USB supply
+5V (Barrel Jack input)	2A
+3.3V	800mA

The BPS features a 3A fuse at its barrel jack input for protecting against severe input overvoltage conditions. The board also features short circuit protections from each power rail to each other power rail on the supply. Although it is obviously not a desired use case of the supply, one can short the +12V to +5V rail, the +12V to 0V rail, the +5V to -12V rail, the +3.3V to 0V rail, or any other combination of power supply rail shorts without breaking the BPS. These protections are accomplished by the internal short circuit protections of the on-board voltage regulator ICs, an on-board Zener diode, and the Micro-USB input power supply itself, in the case where the BPS is powered from a Micro-USB and set to output a +5V rail. The board was designed and tested to be robust in the face of undesirable and otherwise damaging power supply connection errors with the understanding that the BPS will be used in a learning environment. Furthermore, the board has been designed to be manufactured using modern automated processes, enabling mass manufacturing and reducing costs. Appendix A includes a system diagram of key power electronic stages of the BPS. Specifically, these stages include a dc-dc synchronous buck converter, a push-pull transformer driver, a multi-winding transformer, and several linear regulators.

II. Power Rail "Jumper Board"

The Jumper Board routes the power rails of one breadboard over to a second, adjacent breadboard. A photograph of the Power Rail Jumper Board is shown in Figure III.

FIGURE III
THIS PCB CONVENIENTLY CONNECTS POWER RAILS BETWEEN ADJACENT BREADBOARDS FOR ELECTRONICS PROJECTS THAT REQUIRE MORE SPACE THAN THAT OF A SINGLE BREADBOARD.

As shown in Figure III, the soldered components required for assembling the Jumper Board are all header connectors. This board can be pre-assembled by an instructor and issued to students, or can act as an excellent candidate for students to learn and practice their soldering skills as their designs become more complex and require additional breadboard space. Since each student using our hardware platform is intended to receive one BPS, a student seeking to power several circuits at once will eventually require a second breadboard for building space and need to provide power to that board as well. The Jumper Board allows for easy, reliable routing of the power rails from the first breadboard to the adjacent breadboard. This helps to reduce common wiring errors when a second breadboard is introduced to a project. The board also provides several convenient power rail test points, clearly labeled on the silkscreen layer of the Jumper Board PCB. This PCB promotes neat building as student projects become more complex. Furthermore, the Jumper Board provides a clear, standard means of sharing power rails between breadboards. The silkscreen layer and orienting, protruding test point tabs allow users to quickly and easily confirm proper power wiring when introducing additional hardware to their projects.

III. PSoC Oscilloscope

Many valuable, hands-on introductory electrical circuit lessons do not require the measurement of time-varying waveforms. Several of the labs in our Electronics FIRST curriculum, for example, are designed with the understanding that most students would not have access to oscilloscopes when building, debugging, and enjoying the laboratory exercises. That said, many interesting and motivating electrical circuit lessons, like audio circuits, involve time-varying waveforms with frequencies on the order of hundreds of Hz to tens of kHz. In these cases, there is immense pedagogical and practical value in having an oscilloscope for measuring time-varying electrical signals for design verification and debugging. Furthermore, experience with electrical measurement tools beyond a simple multimeter is useful for the development of young engineers.

Motivated by the considerations described above, our electronics platform includes an oscilloscope measurement module. The PSoC Oscilloscope leverages existing hardware in our Electronics FIRST curriculum, a PSoC "Carrier" PCB, which is a platform on which students learn embedded programming lessons using an Infineon PSoC 5LP prototyping kit [8]. An oscilloscope "shield" is installed on the PSoC Carrier PCB, providing standard BNC connectors for two oscilloscope channels and a signal generator. A photograph of the PSoC Oscilloscope is shown in Figure IV.

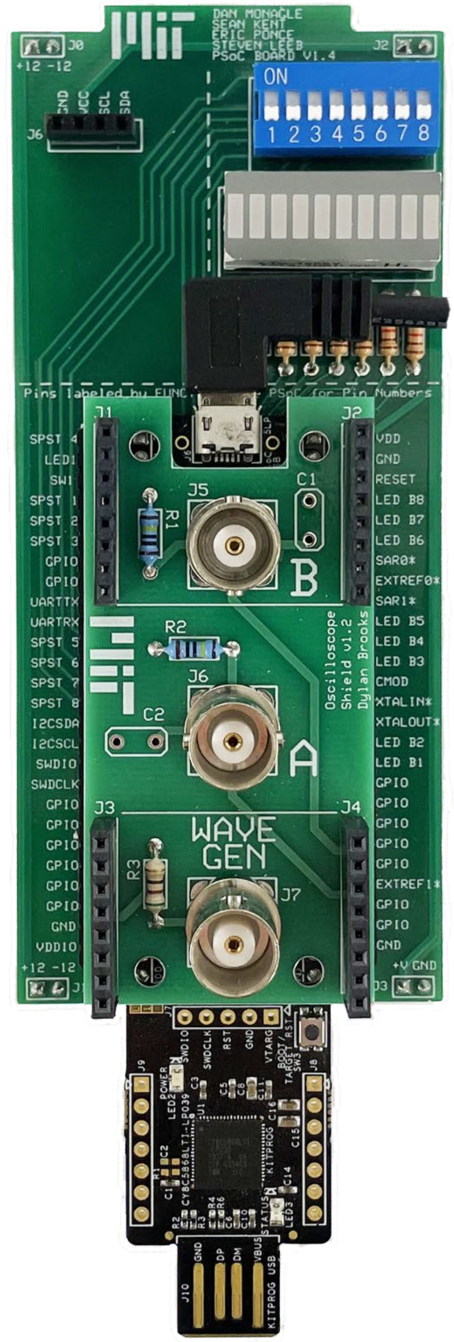

FIGURE IV
THE PSOC OSCILLOSCOPE FEATURES TWO CHANNELS AND A SIGNAL GENERATOR.

Firmware, provided to instructors and students, is programmed onto the hardware and configures the board to act as a simple oscilloscope. Once the hardware is programmed, users make a USB connection from the PSoC Oscilloscope to a personal computer and run a graphical user interface (GUI) program that displays the waveforms on each oscilloscope channel and allows for configuration of the waveform generator. The PSoC Oscilloscope GUI includes automatic measurement functionality for measuring a signal's frequency, period, minimum and maximum voltages, and peak-to-peak amplitude. The GUI also includes math features for adding, subtracting, and multiplying measured signals. Both the firmware and GUI program mentioned above were originally provided by Cypress/Infineon [9] and have been modified by our Electronics FIRST course staff. A sample screenshot of the GUI running on a personal computer is shown is Figure V.

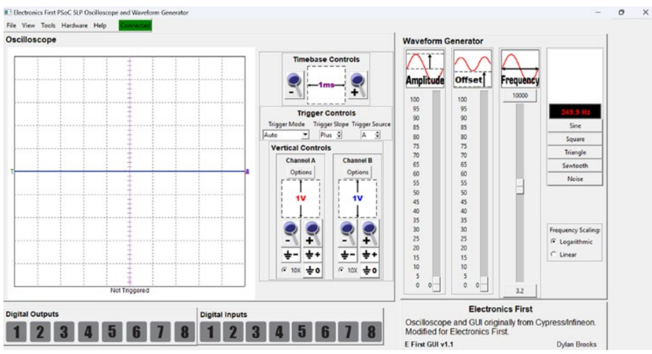

FIGURE V
THE PSOC OSCILLOSCOPE GUI FEATURES A WAVEFORM VIEWER, HORIZONTAL AND VERTICAL SCALING CONTROLS, AND A WAVEFORM GENERATOR INTERFACE.

The PSoC Oscilloscope features BNC connectors for its two probe channels and its signal generator channel, allowing students to work with standard passive oscilloscope probes and signal generator cables. The features of those standard probes, like 10x attenuation of an input signal can be leveraged by students and instructors while using the PSoC Oscilloscope. The PSoC Oscilloscope reliably measures signals on the order of tens of kHz. This PCB is a wonderful tool for measuring interesting and exciting audio circuits, where students can experience the illuminating exercise of measuring and visualizing waveforms that they are simultaneously hearing through a speaker. Furthermore, since the firmware programmed onto the PSoC Oscilloscope hardware is provided to instructors and students, users have the option to delve into the more-advanced, underlying embedded hardware details of digital oscilloscope measurement functions, such as analog-to-digital conversion and serial communications.

DEMONSTRATIONS

This section demonstrates example uses of hands-on electronics activities using our hardware platform. This section showcases some of the capabilities and features of the BPS, Jumper Board, and PSoC Oscilloscope along with two of the laboratory exercises included in the wider Electronics FIRST curriculum. During a typical term-length offering or a shorter workshop, an instructor or instructors work with participants to design and build an Electronics FIRST circuit board, as shown in Figure VI.

FIGURE VI
ASSEMBLING AN ELECTRONICS FIRST PCB.

An example demonstration setup of the electronics platform is shown in Figure VII.

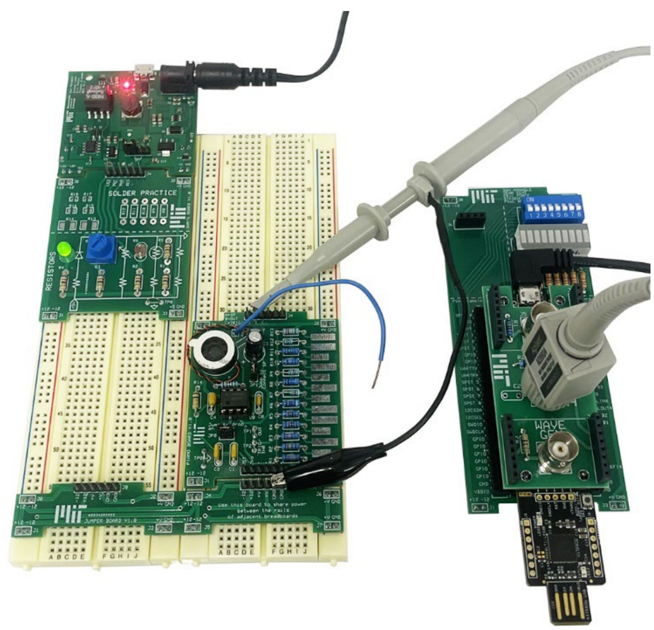

FIGURE VII
THE BPS AND JUMPER BOARD POWER TWO LABORATORY EXERCISES FROM ELECTRONICS FIRST, WHILE THE PSOC OSCILLOSCOPE MEASURES THE OUTPUT OF AN OSCILLATOR CIRCUIT.

In our example demonstration, the BPS power indicator LED is illuminated as the BPS is receiving input power from a 12V barrel jack power supply that is plugged into a wall outlet. A standard passive oscilloscope probe has been installed on the Channel A BNC connector of the PSoC Oscilloscope, and the PSoC Oscilloscope is connected via its Micro-USB connector to a personal laptop. Just underneath the BPS, an assembled PCB from the Electronics FIRST “Dividers” laboratory exercise, in which students learn about Ohm’s Law, LEDs, and variable resistors, is included and powered by the BPS. On the Dividers PCB, one can see an illuminated LED flanked by a potentiometer, photoresistor, and other resistors.

Illustrating the convenience of the Jumper Board, a second breadboard is placed next to the first, and the Jumper Board is installed across the bottom of both breadboards, routing all power rails from the BPS over to the second breadboard. The second breadboard powers an assembled PCB from the “Oscillators” laboratory exercise, in which students learn about tone generation using a 555-timer IC and resistor-capacitor combinations.

The Oscillators exercise is a prime example for showcasing a PSoC Oscilloscope measurement. The tones generated by the Oscillators PCB do not lend themselves to multimeter measurements, as these waveforms oscillate at frequencies in the human audio range of approximately 20Hz to 20kHz. As depicted in Figure VII, the probe tip from the passive probe on the PSoC Oscilloscope has been installed on a test point of the Oscillators board that allows for measurement of the output of its 555-timer IC. When the long wire extending from the Oscillators PCB is pressed against one of the exposed electrical “piano key” contacts on the right-hand side of the PCB, a tone is generated that is audibly heard through the on-board speaker. As shown in Figure VIII, a waveform is displayed in the waveform viewer section of the PSoC Oscilloscope GUI, allowing a user to visually inspect an oscillating waveform while listening to it. The auto measurement window displays that the Channel A signal is an approximately 450Hz wave with a peak-to-peak amplitude of approximately 2V.

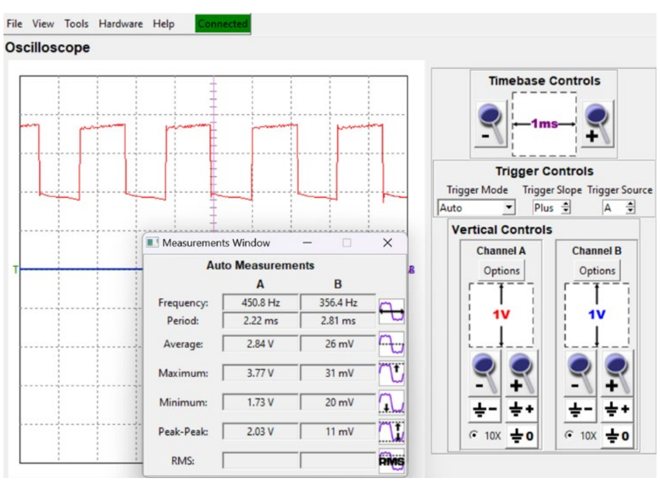

FIGURE VIII
THE PSOC GUI WAVEFORM VIEWER DISPLAYS THE TIME-VARYING OUTPUT OF A 555-TIMER, WHICH IS PRODUCING AN AUDIBLE TONE FROM THE OSCILLATORS PCB.

CONCLUSION

This paper presented power supply and measurement modules that catalyze electrical circuit STEM outreach efforts. An electrical circuit education integrates rigorous mathematics and physics with an opportunity for practical and motivating hands-on exercise. The Electronics FIRST exercises give students a chance to see the physical phenomena and the electrical circuits that harness these phenomena as building blocks for creative design. The power and measurement systems described here provide basic tools of good quality and capability for allowing students anywhere to build and explore circuits.

ACKNOWLEDGMENT

This work is not affiliated with the FIRST nonprofit organization, but we are inspired by the example of STEM outreach and the lasting impact of Professor Woodie Flowers on so many generations of engineers. The authors would like to thank the many students and instructors who have contributed to the design, testing, development, and deployment of our Electronic FIRST curriculum and hardware platform, especially Sean Kent. The authors would like to thank Greg Landry and Dr. Patrick Kane Ed.D. of Infineon. The authors gratefully acknowledge the support of the MIT Portugal Program, Texas Instruments, and Coilcraft.

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APPENDIX A: BPS POWER ELECTRONIC SYSTEM DIAGRAM