



Davidson, Z. C. M., Dang, S., & Vasilakos, X. (2024). Blended Laboratory Design Using Raspberry Pi Pico for Digital Circuits and Systems. *IEEE Transactions on Learning Technologies*, 17, 1170-1183. Article 10423829. <https://doi.org/10.1109/TLT.2024.3363230>

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Blended Laboratory Design Using Raspberry Pi Pico for Digital Circuits and Systems

Zoe C. M. Davidson, *Member, IEEE*, Shuping Dang, *Senior Member, IEEE*, and Xenofon Vasilakos, *Member, IEEE*

Abstract—Raspberry Pi Pico, based on chip RP2040, is an easy-to-use development micro-controller board that can provide flexible input/output functions and meets the teaching needs of basic electronics to first-year university undergraduates. This paper presents our blended laboratory design using Raspberry Pi Pico for the course unit Digital Circuits and Systems. Considering the impacts of Coronavirus Disease 2019 (COVID-19) and the reduced number of students attending the in-person laboratory, we provide an alternative approach using an online Raspberry Pi Pico simulator produced by Wokwi for those students who cannot attend the physical laboratory. The entire laboratory is designed by design-based learning (DBL) pedagogical methodology and consists of three dependent sessions. Throughout the three laboratory sessions, first-year undergraduates are expected to understand the basic digital logic and electronic circuits by building a simplified interactive traffic light controller system using Raspberry Pi Pico and Python programming. The intended learning outcomes, full details of the blended laboratory design, and the laboratory design evaluation results are given and discussed in this paper to verify the effectiveness of the blended laboratory design using Raspberry Pi Pico. By analyzing the empirical data collected from laboratory participants, the effectiveness of the proposed blended laboratory design can be well supported, and all intended learning outcomes are successfully achieved subject to the impacts of COVID-19.

Index Terms—Virtual labs, educational simulations, personalized e-learning, blended teaching, laboratory design, digital circuits and systems, COVID-19, Raspberry Pi Pico.

I. INTRODUCTION

THE knowledge of electronic components, circuits, and digital logic is fundamental and essential for undergraduates enrolled in a variety of degree programs including electrical engineering, electronic engineering, mechanical engineering, and automation [1]. At the Department of Electrical and Electronic Engineering, University of Bristol, we offer a 20-credit introductory course unit *Digital Circuits and Systems* (EENG14000) for first-year undergraduates to cover the design and implementation of basic electronic circuits and systems based on digital logic [2]. Throughout this course unit, undergraduates are expected to learn how basic electronic components, e.g., micro-controllers, light-emitting diodes (LED), resistors, push-buttons, potentiometers, and jumper wires, are interconnected to realize complex digital logic and functions by computer programming.

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Theoretical learning from lectures is not enough for achieving the intended learning outcomes of such a practical course unit, and therefore the associated laboratory design and experiments are necessary for building practical skill sets [3]. However, the outbreak of Coronavirus Disease 2019 (COVID-19) in 2019 created a large challenge for the organization and delivery of laboratory work at universities. The challenges for teaching laboratories included the need to account for social distancing, reduced number of students present on campus, and strict regulations of a risk assessment [4]. All these impacts brought by COVID-19 made conventional laboratory work for Digital Circuits and Systems difficult and inadequate. As a result, there is a dire need for appropriate adjustments to the existing laboratory design [5]–[9].

Even with the passing of COVID-19, the need for a blended and hybrid approach to higher education remains an important challenge to modern universities. In fact, our institution as well as several others world-wide are in the process of designing distance-learning academic curricula in engineering, with Digital Circuits and Systems being one of the course units that is ready to tackle the challenge based on our design and experience documented here. The development of distance learning is vital in a time with growing extreme weather events, a desire for flexible learning, to meet the needs of students' physical and mental health, and in the event of another global pandemic [10]–[12]. The development of distance laboratories is, in particular, important and challenging due to the requirement of complex and costly equipment. A review of contemporary virtual/remote laboratory implementations has revealed that there are quite a few positive impacts of laboratory activities on students' achievements and interests and has explored the advancements in technology that have led to the development of virtual and remote labs, offering extra pedagogical benefits to students [13]. As such, this paper aims to demonstrate a methodology for teaching in-person and online laboratories in a parallel manner, providing the tools and experience should there be a requirement for this again.

The challenges caused by COVID-19 led to the proposal of a blended laboratory design for the course unit Digital Circuits and Systems implemented at University of Bristol, Bristol, UK. In contrast to other hybrid teaching occurring at this time, this novel blended response allowed us to deliver laboratories simultaneously to students both on campus and remote. Students could, for the first time, simultaneously be online and on-site with physical equipment or simulation environments. The unique advantage of the fully hybrid delivery is that we were able to have step-by-step videos alongside live demonstrations,

using double camera videos showing the physical interaction with the micro-controller and the on-screen results.

Different from the laboratory in previous years, we adopt Raspberry Pi Pico based on chip RP2040 as the development micro-controller board, Python as the programming language, and an online Raspberry Pi Pico simulator created by Wokwi (<https://wokwi.com/>) as an alternative to a physical laboratory for those who cannot attend laboratory sessions on campus or access at home lab kits. Due to the powerful functionality, flexible setup, low cost, and easy access of Raspberry Pi Pico, we can adapt to a much more flexible and easy-to-implement blended laboratory design for Digital Circuits and Systems. Specifically, the pedagogical contributions of the proposed blended laboratory design include

- Parallel laboratory delivery options are in place to cope with various negative impacts of COVID-19 on face-to-face teaching.
- Innovative hardware and software are jointly employed to assist blended laboratory organization and delivery, including the creation, distribution, and delivery of resources needed for a purely hybrid and blended learning environment.
- Laboratory organization and delivery become much more flexible and resilient to COVID-19 pandemic development and the changes in related regulations on campus.
- The consistency of most intended learning outcomes can be maintained for students attending both physical and online laboratories.
- The laboratory delivery becomes customized and can meet heterogeneous educational demands from students.
- The self-learning materials of the Raspberry Pi family and Python are more accessible and easy to understand for first-year undergraduates who have limited knowledge of electronics and programming.
- Being familiar with Raspberry Pi Pico and Python can be helpful for other higher-year course units and projects.

To evaluate the effectiveness of the proposed blended laboratory design, we carried out an after-laboratory survey to collect empirical data from laboratory participants. The top insight gained from the empirical data collected is that the quality of the laboratory is not compromised by implementing the blended laboratory design. The intended learning outcomes of the course unit can be maintained regardless of whether students choose to attend physical laboratory or carry out online laboratory relying on the results on the simulator. The evaluation results collected from the laboratory participants also verify the effectiveness of the blended laboratory design in terms of the aforementioned pedagogical contributions.

The rest of this paper is organized as follows. We present the laboratory design basics and outline in Section II, in which we also expatiate on the impacts of COVID-19 on laboratory teaching and the advantages of employing Raspberry Pi Pico and Python. The details of the three-session laboratory design are given in Section III. The alternative approaches of online laboratories for students who cannot attend physical laboratory sessions are detailed in Section IV. To verify the effectiveness of the proposed blended laboratory design, we carry out

a rigorous evaluation and discuss the evaluation results in Section V. Finally, the paper is concluded in Section VI.

II. LABORATORY DESIGN BASICS AND OUTLINE

Digital Circuits and Systems (EENG14000) is a 20-credit course unit, lasting for 24 weeks for 100-150 first-year undergraduates enrolled in B.Eng/M.Eng degree programs with Department of Electrical and Electronic Engineering, University of Bristol. The associated laboratory sessions are designed to assist in achieving the intended learning outcomes of Digital Circuits and Systems and particularly to enhance the practicality of the course unit. As this unit is designed for the first-year undergraduates, the participants of this course unit are assumed to have a limited knowledge of electronics and that they will only understand the operation of simple linear circuits consisting of power source, resistor, diode, switch, and so on.

A. Intended Learning Outcomes and Methodology

According to the official course description of Digital Circuits and Systems, [2], there exist fifteen intended learning outcomes, among which most of these will to be achieved by lecturing, while some of these shall be achieved by a practical laboratory. We have extracted and list those intended learning outcomes relevant to the practical laboratory as follows:

- Describe the internal and external operation of a simple central processing unit (CPU) at the fetch/execute level.
- Create and debug simple Python programs.
- Describe the principles of a high-level language, compilation and linking

These intended learning outcomes form the foundation for this course unit's laboratory design and teaching objectives.

In this regard, we adopt design based learning (DBL) as the pedagogical methodology for delivering the laboratory, aiming at fostering the hands-on and algorithmic thinking capabilities of first-year undergraduates [14]. Adopting a similar framework and key elements of the DBL methodology designed in [15], we depict our tailored DBL framework for delivering the laboratory in Fig. 1. The DBL methodology is problem-oriented, and therefore it is of paramount importance to define the design problem for participants in the laboratory [16]. We define the core design problem as to *build a simplified interactive traffic light controller system using Raspberry Pi Pico and Python programming language* [17].

Considering the stringent time allocated to laboratory work and the fundamental nature, we adopt the independent working mode and do not arrange team/group work. Furthermore, the instruction-based laboratory mode is also adopted due to the limited knowledge background of first-year undergraduates [18].

B. Impacts of COVID-19 on Laboratory Teaching

COVID-19 has yielded a series of negative impacts on teaching and campus life over the past few years [19]–[21]. The most obvious impact is the reduced students' presence due to travel restrictions and quarantine measures. As a result,

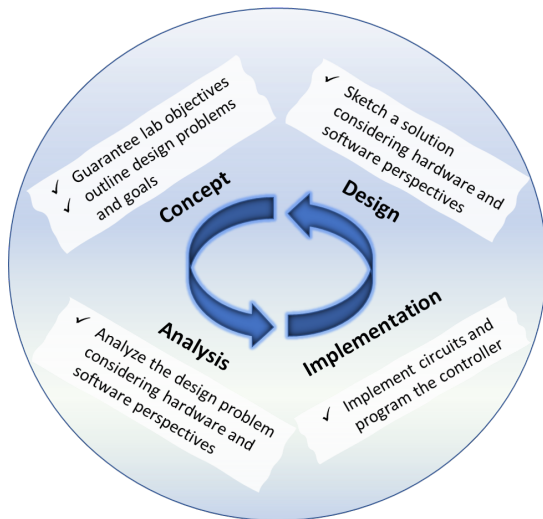


Fig. 1: Tailored DBL framework with four key elements for the laboratory delivery for the course unit of Digital Circuits and Systems.

online or hybrid teaching becomes imperative for engaging remote student cohorts who cannot be present on campus. Hybrid teaching continues to be relevant in the post-COVID-19 era for various reasons. Factors like temporary travel visa issues or illness may hinder students from attending in-person laboratories, reinforcing the need for this adaptable educational approach. Teaching practical laboratories, in addition to theoretical lectures with practical applications, without the physical presence of both the teaching personnel and the trainees (i.e., the students) is not a trivial task. Moreover, this is further aggravated by the lack of prior knowledge and experience from first-year students whose secondary school education was also impacted by the pandemic. Based on our experiences from the two academic years occurring during the pandemic, students need immediate and individualized support to complete more basic tasks such as how to plug-in equipment (e.g., capacitors, LEDs, and so forth), or to make the necessary electrical connections. While these tasks may seem trivial in the eyes of slightly more experienced learners, such learning has been missed at a secondary level due to the remote nature of teaching during the pandemic. Moreover, students can face problems that remote instructors cannot identify, such as hardware failures or numerous software/hardware incompatibility issues.

These challenges are the tip of the iceberg compared to the challenges of teaching programming remotely. Remote learners typically find it difficult to digest complex programming syntax and keywords, including good coding practices and philosophies [22]. Detailed step-by-step instructions on installing the necessary software may be helpful in the absence of help, yet delays the actual teaching, as teaching staff need to engage in time-consuming individual calls with students. In addition to the incompatibility issues due to using heterogeneous infrastructures (i.e., the students' own PCs), other logistic and administrative challenges render additional difficulty and cost for conducting remote laboratory teaching and activities. As a result, we need to act fast and teach

the same content with online simulation environments for engaging online student cohorts who are not physically present in laboratories.

C. Hardware and Software Selection

A Raspberry Pi Pico is a low-cost but high-performance micro-controller board with flexible digital interfaces. This was chosen to replace the previous choice of a Teensy 3.6, which is an Arduino-based micro-controller programmable in C language. Both micro-controllers pose educational advantages and can have real-life applications. However, Pico provides a series of advantages, which we analyze below.

Firstly, Pico's cost is far more affordable for students who cannot join laboratory activities on campus and/or will need to purchase experimental equipment themselves. Moreover, Pico consumes less power. Despite these two advantages, Pico does not compromise regarding chipset capacities. In fact, Pico's capabilities can meet, if not exceed, those of the Arduino's or Teensy's high capacity chipsets¹

Secondly, Pico is slightly easier to access worldwide, which is vital in the case that the micro-controller needs to be distributed to every student worldwide upon a return to a challenging lock-down situation².

In addition to the above, our choice for Pico is driven by many more technical advantages related to teaching needs extending beyond just our course unit, as Raspberry Pi Pico qualifies for future student projects and other teaching units. Raspberry Pi Pico offers a series of programmable input/output pins that can be used to simulate multiple interfaces and protocols. These pins can be used to offload complex tasks to a background process. This offers a critical educational advantage for students during their later years of study, as a part of a more comprehensive educational framework within the department's curriculum. Moreover, Pico is easier to program. It allows users to write and save codes directly to the board. A student needs to use Microsoft's Visual Studio Code. Alternatively, if we wish to impose less automation for training purposes, using a terminal with a plain text editor, downloading, and building a project into a UF2 file manually copied to Pico is straightforward.

Finally, our choice was driven by the need to decouple C programming from micro-controller programming for first-year students. Python's intrinsic development eases remote teaching scenarios, particularly for those students who struggle more. Unlike C, Python has fewer keywords and a more straightforward syntax. Meanwhile, any performance-related disadvantages for Python are not prohibitive at this stage, as students will later attend a specially designed course unit on efficient C programming.

D. Laboratory Design Outline

Adhering to the intended learning outcomes and following the above motivations, we propose and summarize a

¹A quantitative analysis with comparisons is provided online through the following link: <https://www.tomshardware.com/features/raspberry-pi-pico-vs-arduino>.

²Last year's attempt to distribute Teensy to some Southeast Asian couriers resulted in considerable delays, causing teaching impediment.

three-session laboratory design outline for Digital Circuits and Systems as given in Table I. The objectives of this laboratory design is to provide an introductory session to micro-controllers, the machine-level operation of a computer and the fundamentals of micro-controller programming. The laboratory is based on the Raspberry Pi Pico board using chip RP2040 and Python for physical computing and is delivered in three sessions with specific developing and programming tasks. More details of the hardware and software requirements and arrangements will be given in the next section.

The three laboratory sessions were carried out over three hours over three consecutive weeks. These sessions are arranged in a related and progressive way so that students can build and upgrade a simplified digital system step by step. Before attending each laboratory session, students were required to watch a laboratory instruction video online, in which the preliminary knowledge for conducting experiments and matters needing attention are imparted. During the laboratory sessions, eight teaching assistants are employed to help with the questions raised from students but are not expected to directly get involved in their laboratory work. After the three sessions, students are asked to write up and submit a brief laboratory report as a formative assignment³. In addition to practical skill sets built through the laboratory work, writing up the brief laboratory report is aimed to equip students with some transferable skills, e.g., academic communication and writing.

III. THREE-SESSION LABORATORY DESIGN FOR DIGITAL CIRCUITS AND SYSTEMS

In this section, we present the full details of all three laboratory sessions, including the design problem formulation, system setups, instructions, circuit schematics, and programming structures. In conjunction with the laboratory design outline given in Table I, this section aims to enable experienced educators to have all necessary details for applying, tailoring, and reproducing the laboratory design based on their needs and scenarios. Throughout all three laboratories a Microsoft Teams meeting room is left open with a presentation showing (i) video cameras showing the live circuit the instructor is working with, and (ii) sharing a screen demonstrating the simulation environment. This presentation is also streamed to TV screens in the laboratory for in-person students to follow. Teaching assistants are present both online and in person to answer questions from students.

A. Session 1: Introduction of Raspberry Pi Pico, Python, and Physical Programming

The first laboratory session is preparatory, giving a full picture of the entire laboratory design and basics of Raspberry Pi Pico, circuit design, and physical programming. Before getting into the technical parts, the teaching team and objectives of all three labs are first introduced. Then, we present the measures

³At University of Bristol, formative assignments do not count for the student's final mark of a course unit. In the context of remote teaching and laboratory, they are specifically implemented for self-testing, progress monitoring, and quality insurance purposes [23].

for guiding and carrying out laboratory activities in a remote manner for those who cannot physically attend the laboratory on campus and do not have hardware equipment at hand because of the impacts of COVID-19. We also introduce and recommend the online Raspberry Pi Pico simulator produced by Wokwi to students and illustrate how to interact and raise questions through Microsoft Planner embedded on Microsoft Teams.

In the first technical part of Lab 1, we explain to students, both present and online, the concepts of micro-controller and micro-computer on a generic basis and then take the RP2040 and Raspberry Pi Pico as concrete examples to expatiate on. In particular, we introduce the basic features and functions of Raspberry Pi Pico, including the flash memory, operational voltage, GPIO pins, as well as ADC, PWM, and a set of supporting communication protocols, i.e., UART, SPI, and I²C. With a pinout diagram of Raspberry Pi Pico, we subsequently detail the micro-USB port, on-board LED, BOOTSEL button, and all brought-out pins of RP2040. We organize the descriptions of all the brought-out pins according to the following categories for clarity:

- **Power related pins:** VSYS, 3V3, and VBUS.
- **Ground pins:** GND and GND/VGND.
- **GPIO pins:** GPxx and GPxx/ADCx.
- **ADC related pins:** ADCx, ADC_VERF, GND/AGND.
- **Enabling pins:** 3V3_EN and RUN.
- **Hardware debugging pins:** SWDIO and SWCLK.

We also explain the reason why some GPIO pins' indexes are missing on the Pico board, e.g., GPIO pins 23, 24, and 25.

With the basic knowledge of Raspberry Pi Pico, in the next part of Lab 1, we show how the Raspberry Pi Pico board can be connected to a PC and becomes ready for Python programming on Thonny, an easy-to-use Python IDE for beginners. This is done by presenting on screen to both the in-person and online students. For the Year 1 student cohort, we start from downloading and installing Thonny step by step until opening the Shell window for programming. Once the software platform has been properly installed and configured, we turn back to the hardware side and physically connect the Raspberry Pi Pico board placed on a breadboard to a PC through a micro-USB cable. We specially highlight the installation of the MicroPython firmware for the first-time connection and remind students to of choose the correct MicroPython interpreter on Thonny. We also show the correct Shell message on Thonny indicating successful connection and identification of the Raspberry Pi Pico board.

When both hardware and software are ready, we start an initial programming task for manipulating the on/off state of the on-board LED of Raspberry Pi Pico that is internally connected to GPIO pin 25. We also wish to use this simple Python program to test the connection between Raspberry Pi Pico and the PC as well as the hardware/software compatibility. This simple program will be run to light up the on-board LED and consists of fundamental codes for importing the Pin object from hardware-specific module `machine`, creating an output Pin object to correspond with the on-board LED that is connected to and controlled by GPIO pin 25, setting the output value of GPIO 25 to be logic 1 to generate a high voltage (3.3

TABLE I: Laboratory design outline and required supporting resources.

Laboratory session	Laboratory objectives	Hardware	Software	Staff	Duration
Lab 1: Introduction of Raspberry Pi Pico, Python, and Physical Programming	<ol style="list-style-type: none"> 1) Understand what a micro-controller is 2) Become familiar with Raspberry Pi Pico, its pinout, and features 3) Connect Raspberry Pi Pico to a PC on Windows and become familiar with Thonny, which is a Python integrated development environment (IDE) 4) Understand the basic concepts of Python: variables, expressions, conditionals, and loops 5) Understand the basic functions that will be used for physical programming 	1x Raspberry Pi Pico board, 1x micro-USB cable, 1x breadboard, 1x PC	Thonny IDE ver. 3.3.13, Wokwi online simulator, Microsoft Teams, Microsoft Planner	1x instructor and 8x teaching assistants	3 hours
Lab 2: Building a Simple Traffic Light Controller	<ol style="list-style-type: none"> 1) Build the circuit of a simple traffic light controller with three LEDs and a pushbutton 2) Read and control general purpose input/output (GPIO) pins of Raspberry Pi Pico 3) Build and run a simple “blinky” program to test the connections of the circuit 4) Understand interrupting for physical programming 5) Build and run a simple traffic light controller program with an interrupt mechanism 	1x Raspberry Pi Pico board, 1x micro-USB cable, 1x breadboard, 1x PC, 3x 220 Ω resistors, 3x red/amber/green LEDs, 1x pushbutton, and some jumper wires	Thonny IDE ver. 3.3.13, Wokwi online simulator, Microsoft Teams, Microsoft Planner	1x instructor and 8x teaching assistants	3 hours
Lab 3: Controlling the Brightness of Traffic Lights	<ol style="list-style-type: none"> 1) Understand the difference between digital and analogue signals 2) Understand the analogue-to-digital conversion (ADC) process 3) Read analogue input signals generated by a potentiometer from an ADC input pin 4) Understand pulse-width modulation (PWM), a method of generating quasi-analogue output signals by Raspberry Pi Pico 5) Update the simple traffic light controller built in Lab 2 by adding a potentiometer to control the brightness of traffic lights 	1x Raspberry Pi Pico board, 1x micro-USB cable, 1x breadboard, 1x PC, 3x 220 Ω resistors, 3x red/amber/green LEDs, 1x pushbutton, 1x potentiometer, and some jumper wires	Thonny IDE ver. 3.3.13, Wokwi online simulator, Microsoft Teams, Microsoft Planner	1x instructor and 8x teaching assistants	3 hours

volts) to light up the on-board LED. A special reminder is given for entering the .py file extension when saving Python programs on Thonny before running them.

Subsequently, we introduce the `while` loop and `sleep` function from module `utime` to have another more complex program that blinks the on-board LED. When introducing the `while` loop, we emphasize the importance of indentation in Python programming language and explain how indentation will affect code execution. Then, we assign the task to the students to have a Python program that blinks the on-board LED for exact eight times. Three coding strategies with different program structures are introduced for realizing the same functionality:

- Use an always-true `while` loop together with an `if` statement and the `break` mechanism based on a counting variable initialized before getting into the `while` loop.
- Use a `while` loop taking a counting variable initialized before getting into the `while` loop as the executing condition of the code block inside the `while` loop.
- Use a `for` loop together with the `range` function.

Through this task and the different coding strategies, we would

like to show that for realizing the same functionality, diverse coding approaches can be adopted with different coding efficiency and readability.

For those students running a virtual Raspberry Pi Pico through the Wokwi virtual environment, they will follow the exact same steps and achieve the same outcome. The only difference is that they do not need to install the Thonny software to complete the simulation.

This introductory laboratory session has been designed to walk students through the first part of the tailored DBL method. Students were introduced to the concepts of the laboratory, and given the foundation knowledge they needed to continue with the laboratory task. They have been introduced to the design problem and goals for the three laboratories.

B. Session 2: Building a Simple Traffic Light Controller

The second laboratory session aims to equip students with the ability to build simple circuits on a breadboard according to circuit schematics and configure GPIO pins of a Raspberry Pi Pico for processing digital signals. We propose to realize the objectives of the second laboratory session by requesting

students to design and build a simplified traffic light controller system, by which the operational status of three traffic lights, represented by three external LEDs, can be controlled by a pushbutton.

At the beginning of Lab 2, we present the design specifications of the simplified traffic light controller that should be realized by the end of Lab 2 using Raspberry Pi Pico and other electronic components on breadboard:

- The traffic light controller consists of red, amber, and green lights as well as a pushbutton.
- Without pressing the pushbutton, the green light is always on, while the red and amber lights are always off.
- Once pressing the pushbutton, the green light should be off after 10 seconds, and then the amber light will be on for 2 seconds. Then, the amber light will be turned off, and the red light should be on for 5 seconds allowing pedestrians crossing the road safely.
- Having been on for 5 seconds, the red light will be turned off, and the green light will remain on until the next time the pushbutton is pressed.

For building the circuit of the simplified traffic light controller, we introduce the basic structure and electric characteristics of several through-hole components, including LEDs, resistors, and a pushbutton. For resistor components, we have introduced a method of reading the resistance values by incorporating the colour rings printed on the component surface. Internal connections of breadboard, types of jumper wires, and wire cutter and stripper are also briefly introduced to ensure that students will carry out electronic laboratory activities in a safe manner. We emphasize that most through-hole LED components need to be connected in series with a 50-200 ohm resistor to a battery in order to limit the flow of current.

By giving the necessary background knowledge, we then demonstrate a simple example for connecting an LED through a resistor to one of the GPIO pins of a Raspberry Pi Pico on a breadboard as shown in Fig. 2. After this, we show the circuit schematic as in Fig. 3 to students and give them the chance to complete the circuit connection on their breadboards by themselves. Once the circuit is built on the breadboard, the hardware platform for the simplified traffic light controller is complete. This is done by simultaneously presenting both a live video of the breadboard and the Wokwi simulation to both in-person and online students.

With the built circuit, we thereupon give the Python programming details of reading and controlling GPIO pins of Raspberry Pi Pico. Similarly, we introduce another blinky program that can control the on/off states of the three external LEDs to impart the programming techniques to students. We can also rely on the observed outcomes of this program to easily test the connection and functionality of the built circuit.

Different from the first simple blinky program in Lab 1, we introduce user-defined Python functions in Lab 2 to organize the second blinky program with a clear structure. We specify the way to create and call a defined function in Python programming language and explicitly point out to programming novices that when defining a function in Python, the defined function will not be automatically executed without calling it. Then, we detail how to create an input Pin object associated

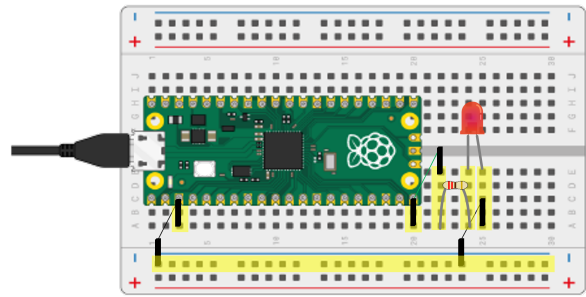


Fig. 2: A simple demonstration for showing how to connect an LED through a resistor to one of the GPIO pins of a Raspberry Pi Pico on a breadboard.

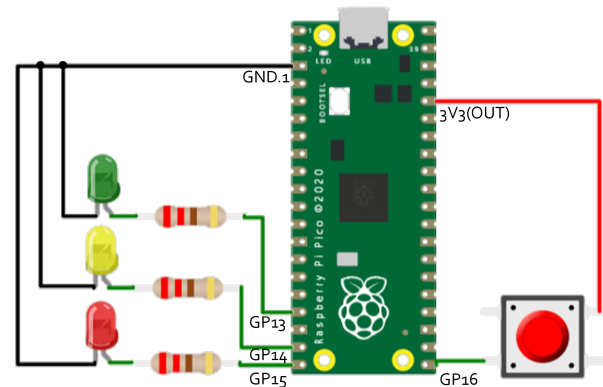


Fig. 3: Circuit schematic of the simplified traffic controller system in Lab 2.

with the pushbutton and set it to be pull-down with low voltage input by default. In our experience, it is relatively difficult for first-year undergraduates to understand the concepts of pull-down and pull-up setups, and therefore we present more explanations and a simple experiment as shown in Fig. 4 to illustrate how this setup affects the terminal behaviors of the floating GPIO pins. We simultaneously broadcast both a live video of the breadboard attached to a multi-meter and the Python terminal to both in-person and online students. Remote students who have their home kits have been provided a handheld multi-meter.

Finally, we demonstrate how the value and toggle properties of created Pin objects can be used to read the input logic value from the pushbutton and swap the on/off status of all three LEDs. When running the demonstration program, students are expected to observe

- Nothing will happen until pressing and holding the pushbutton.
- Holding the pushbutton makes all three LEDs blink.
- Releasing the pushbutton turns off all three LEDs.

In addition, before leaving students to program on their own, we introduce one of the most prominent features of physical programming: Interrupting. We include the concept and motivation of interrupting, as well as the ways to create an interrupt request and a callback function (a.k.a., interrupt handler) by Python.

For those students running a virtual Raspberry Pi Pico

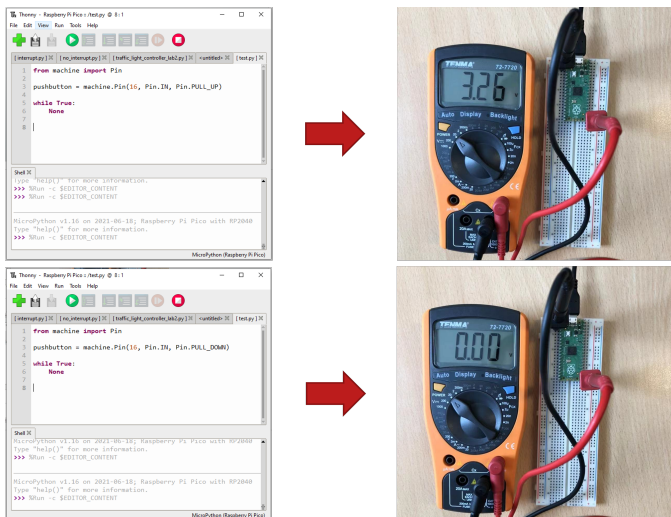


Fig. 4: A simple experiment for illustrating how pull-down and pull-up setups affect the terminal behaviors of floating GPIO pins.

through the Wokwi simulation environment, they will follow the exact same steps and achieve identical outcomes. The only difference is that they will not build a physical circuit, but will create a virtual one, instead.

Equipped with the advanced programming knowledge of configuring GPIO pins and interrupting, students are free to design and program on their own adhering to the given design specifications in the rest of Lab 2.

This laboratory session has been designed to walk students through the second, third, and fourth sections of the tailored DBL method. Students have learned about design in lectures, through the use of circuit diagrams, and the through the use of online simulators such as Wokwi. This learning allows students to sketch a solution while considering hardware and software perspectives. Students then learned how to implement their designs by building their circuits and programming the controller during the second laboratory. Students work independently in an instruction-based laboratory mode, i.e. they can approach tutors with specific questions and to receive advice when needed, rather than being guided through the laboratory. Finally, students were able to analyze the effectiveness of their design and implementation by testing the operation of their circuits and programming. Students then repeated the design based learning loop to debug and solve problems.

C. Session 3: Controlling the Brightness of Traffic Lights

The third laboratory session aims to teach advanced features of Raspberry Pi Pico and the methods to read analogue input and generate quasi-analogue output. Overall, the experiments of Lab 3 is based on the built circuit and program in Lab 2. Analog-to-Digital Converters (ADC) and Pulse Wave Modulation (PWM) features are involved in the investigations of this laboratory session. In particular, students are expected to upgrade the functionality of the simplified traffic light controller built-in Lab 2 by adding a new functionality of controlling the brightness of LEDs through a potentiometer.

We achieve the goals of Lab 3 by first introducing the concepts of digital and analogue signals as well as their

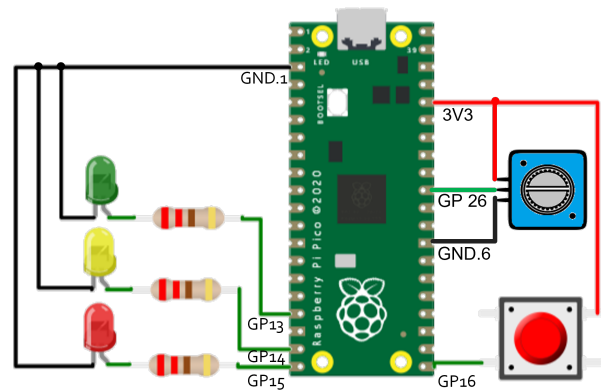


Fig. 5: Circuit schematic of the simplified traffic controller system for upgrading in Lab 3.

differences. Then, we introduce the typical ADC process comprised of sampling and quantization, by which we also stress the impacts of sampling rate and quantization resolution on the accuracy of the ADC process. By taking that Raspberry Pi Pico expresses logic 1 and logic 0 by 3.3 volts and 0 volts as an example, we present a concrete case study to show how an analogue voltage signal with a given value between 0 and 3.3 volts can be converted to a three-bit digital sequence.

To generate an analogue voltage signal, we detail the structure and usage of a through-hole potentiometer component and simply regard it as a voltage divider for increased understanding by first-year undergraduates. Subsequently, we again emphasize that there only exist three special ADC pins on the Raspberry Pi Pico board, i.e., GPIO pins 26, 27, and 28, that can be configured to serve as ADC pins and receive analogue voltage signals.

By giving all background knowledge, we present the circuit schematic for upgrading in Lab 3 as shown in Fig. 5. Compared to the circuit schematic for realizing in Lab 2 as given in Fig. 3, the only update in hardware is to connect the three leads of a potentiometer to the three pins of Raspberry Pi Pico so that the analogue voltage input from the middle lead of the potentiometer can be properly read.

After upgrading the hardware circuit on the breadboard, we utilize a simple Python program to show how the analogue input generated by the potentiometer connected to GPIO pin 26 can be read through the built-in ADC of Raspberry Pi Pico and printed out through the Shell on Thonny by the print function. We specifically introduce the creation of the ADC object relevant to the potentiometer connected to GPIO pin 26 and the calculation of the 16-bit quantized voltage approximating the analogue input voltage by reading the analogue input value.

Knowing how to read analogue input is not enough for Lab 3. Moreover, we are interested in generating a quasi-analogue output by Raspberry Pi Pico, i.e., an output voltage between 0 and 3.3 volts. For this purpose, we then give the concepts of pulse and duty cycle and explain the principle of PWM for generating quasi-analogue output according to a given duty cycle. A simple demonstration program is followed to implement PWM in Raspberry Pi Pico through Python pro-

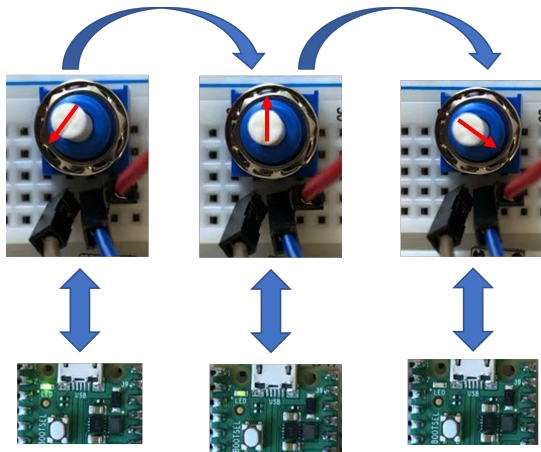


Fig. 6: Observation of the changes of the brightness of the on-board LED by rotating the knob of the connected potentiometer.

gramming. Importing and creating the PWM object pertaining to the on-board LED connected to GPIO pin 25 is introduced, following which setting up pulse frequency and using the duty property are also shown to laboratory participants. When running this simple Python program and rotating the knob of potentiometer, students are expected to observe the changes of the brightness of the on-board LED as shown in Fig. 6. This is done by simultaneously presenting both a live video of the breadboard and the Wokwi simulation to both in-person and online students.

After this stage, we believe that all necessary backgrounds of hardware and software for upgrading the traffic light controller system with the brightness controlling functionality have all been imparted to laboratory participants. Therefore, we present the upgrading specifications of Lab 3:

- Provide an additional and unified controlling interface to administrators by introducing a potentiometer for adjusting the brightness of red, amber, and green traffic lights.
- Keep all the other functionalities of the traffic light controller built in Lab 2 the same.

Laboratory participants are then free to design and program on their own adhering to the given upgrading specifications in the rest of Lab 3.

For those students running a virtual Raspberry Pi Pico through the Wokwi simulation environment, they will follow the exact same steps and achieve the same outcomes. Students will expand their Wokwi simulated circuit from Lab 2 to add the required components for Lab 3.

Before ending the three laboratory sessions, we finally demonstrate three advanced design examples by Raspberry Pi Pico for stimulating further interest:

- A burglar alarm equipped with a motion sensor, a LED, and a buzzer.
- A robotic car with light sensors and motors designed to follow a line.
- A home weather station equipped with a temperature sensor, a humidity sensor, and a liquid-crystal display (LCD) screen.

Through these three design examples, we send a clear message

to the laboratory participants that by obtaining the basics through these three laboratory sessions, they should have the ability to design and build something even more complex and interesting by themselves. Several in-depth study materials and websites are also recommended afterwards, including the detailed datasheet and software development kit (SDK) of Raspberry Pi Pico as well as the documentation of the MicroPython interpreter.

This last laboratory session has been designed to guide students through another iteration of the tailored DBL method. The delivery method and laboratory organization are almost the same as Lab 2 for being consistent.

D. Laboratory Assignment

After completing the three laboratory sessions, both in-person and online laboratory participants are suggested to write up a brief laboratory report to wrap up the design in the three laboratory sessions and show the understandings of electronic circuits design and physical programming. The written report should be submitted in about two weeks after Lab 3. The laboratory report consists of two sections. In the first section, a complete description of the hardware and software design, including a circuit photo and Python code, should be provided. Meanwhile, strict format and submission requirements are also specified for the brief laboratory reports. To encourage students to adhere to these strict requirements, we explain in writing that these writing and submission requirements look like red tape and might be quite tedious to some. However, it is quite common for technicians and researchers to write reports in such a manner, and in the future, students might be in these roles and should therefore get used to them.

In the second section of the report, students are supposed to answer six questions for testing different aspects of electronic circuit design and physical programming:

- **Question 1:** Four resistor components with different color rings are given, and students are required to tell the resistance values of these resistor components.
- **Question 2:** If we must use the pull-up setup for the pushbutton in Lab 2, students need to specify what change(s) should be made on the circuit to ensure proper functionality of the pushbutton.
- **Question 3:** For the blinky program used in Lab 2, students need to tell what will happen when commenting out the `sleep` function and explain the observed phenomenon.
- **Question 4:** A Python program realizing the similar press-and-toggle functionality without interrupting is given, and students are expected to tell whether it is still advantageous to apply to interrupt in this regard.
- **Question 5:** Assuming a four-bit electronic system using 0 and 5 volts to represent logic 0 and logic 1, students are required to manually convert a given analogue voltage input value to a digital sequence of four bits.
- **Question 6:** Students are asked to reduce the pulse frequency of PWM to 10 Hz for the Python program in Lab 3 and explain the observed phenomenon when rotating the knob of the potentiometer.

IV. ALTERNATIVE ARRANGEMENTS OF ONLINE LABORATORY

In order to mitigate the impacts of COVID-19, or any other reason that may affect the in-person attendance of students, and achieve most of the intended learning outcomes of the course module of Digital Circuits and Systems, we make a set of special arrangements for the laboratory delivery. These arrangements also facilitate the online laboratory teaching and can serve as a backup plan for unexpected policy changes in traveling and campus opening. In addition, both the in-person and online laboratory deliveries constitute a blended laboratory design, allowing engaging students with diverse learning conditions and environments.

Before the start of the new academic year, the school collates all required electronic devices and components as well as other auxiliary equipment in a home lab kit. The home lab kit for the Year 1 student cohort enrolled in the electrical and electronic engineering degree program includes the basic electronic components, e.g., LEDs, resistors, capacitors, pushbuttons, potentiometers, wires, batteries, a Raspberry Pi Pico board, and a multimeter, which should be sufficient for carrying out all laboratory activities throughout the three laboratory sessions of Digital Circuits and Systems. The home lab kits are distributed to students at the beginning of the academic year. The home lab kits allow students to safely carry out low-power electronic designs and experiments at home and form the cornerstone of the blended laboratory design.

On the other hand, due to international logistics and cost reasons, we cannot guarantee that all students will have their home lab kits before the first laboratory session. For those students working remotely without home lab kits, we recommend using the online Raspberry Pi Pico simulator produced by Wokwi (<https://wokwi.com/>). This Raspberry Pi Pico simulator is built using the RP2040js library, and most of the important features of Raspberry Pi Pico have been implemented by the online simulator. The simulated results produced by this online simulator are verified to be reliable and close to the practical results by extensive checking and testing. More importantly, Python programming and the MicroPython compilers are supported by this online simulator. All these prominent features of the simulator satisfy the demands of our laboratory design, making it an ideal option to be adopted as an alternative. Accordingly, we also compile an introduction document to cover the basics of using this online simulator, including

- Find the website, create an account, and create a project on Wokwi.
- Code Raspberry Pi Pico by Python programming by the Wokwi simulator.
- Create, build, and code a circuit by the Wokwi simulator.
- Simulate a Raspberry Pi Pico connected to an external circuit by the Wokwi simulator.

In terms of laboratory administration, different from previous years, we split the entire student cohort into two groups for conducting in-person and online laboratories, respectively. During the three-week laboratory period, two parallel three-hour sessions are arranged in each week. One session is

the same as a conventional laboratory session with students working in the Main Electrical Laboratory on campus, while the other session is organized online via Microsoft Teams for those working remotely. Participants can interact with teaching staff in the online sessions and raise questions through Microsoft Planner on the corresponding laboratory channels created on Microsoft Teams. Laboratory teaching assistants are arranged to help with these questions and guide online laboratory activities.

Also, three pre-recorded videos regarding the three laboratory sessions were uploaded to Blackboard Learn one week earlier to allow students to have sufficient time to prepare for the laboratory sessions. Each session's laboratory objectives and key instructions are given in conjunction with simple demonstrations in these pre-recorded videos.

Despite the best effort, we admit that these alternative arrangements of an online laboratory might not be fully equivalent to the in-person laboratory, and the learning experience would not be exactly the same for those remotely participating in laboratory sessions. This is due to more intangible aspects of working in a laboratory environment such as working with others, becoming comfortable with a working laboratory, and crucial social and team working skills. Therefore, students are encouraged to attend the laboratory sessions on campus if they can and should not misuse these alternative arrangements to get around the in-person sessions by simply following the online sessions. In other words, the parallel online laboratory sessions are only backups for those who really cannot attend in-person sessions for necessary reasons. To avoid misusing the online alternatives, we require students who miss one of the three in-person laboratory sessions to participate in remedial laboratory sessions at the beginning of the next academic year⁴. However, it should also be admitted that there are advantages to maintaining a hybrid learning platform including the support of students who are struggling with their physical or mental health, need a higher level of flexibility in their learning, or are unable to come to in-person sessions for any number of reasons.

V. EFFECTIVENESS EVALUATION OF LABORATORY DESIGN AND DISCUSSION

To evaluate the effectiveness of the proposed blended laboratory design, we carried out a survey and asked students to complete a brief questionnaire upon the conclusion of the laboratory assessment. This questionnaire was designed to evaluate the overall satisfaction and whether the intended learning outcomes have been achieved under the impacts of COVID-19. The questions presented in the questionnaire are given as follows:

- 1) Did you attend (1) all physical labs, (2) all online labs, or (3) a mix of physical and online labs.

⁴The remedial laboratory sessions are required for the practical hour component of the Electronic and Electrical Engineering degree at the University of Bristol. All students must fulfill a minimum number of in-person laboratory hours. These sessions help students familiarize themselves with the layout of the undergraduate laboratory and its operations before entering the second year of their degree. Additionally, students who could not obtain their home kits due to international logistics need these sessions to learn practical skills such as wire stripping, breadboard layout, and how to use an oscilloscope.

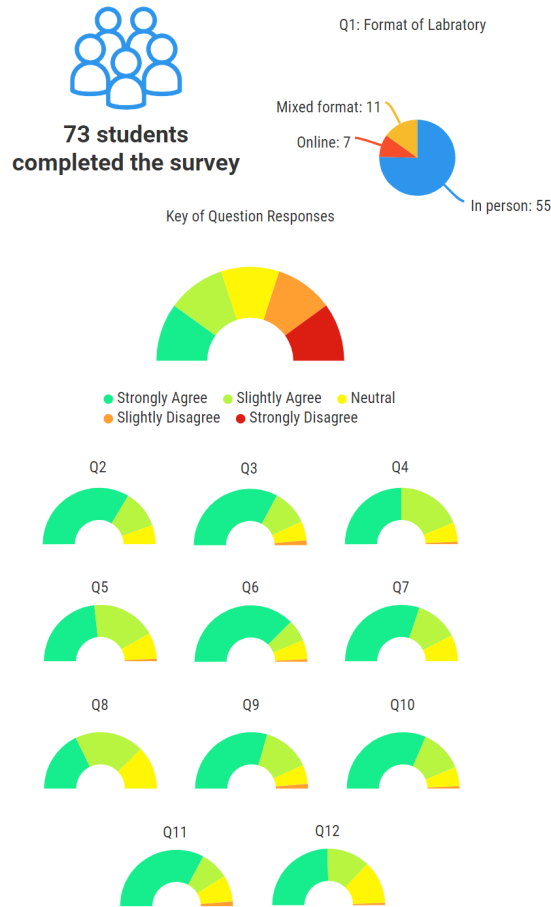


Fig. 7: Subjective data collections of Q1-Q12 in the questionnaire.

- 2) When working on the laboratory activity, I felt well supported.
- 3) I found that the laboratory guidelines were clear, and I could easily follow the related laboratory exercises.
- 4) I have been able to connect between key ideas in the lecture and the laboratory activity.
- 5) I feel confident at the thought of completing laboratories in second year after completing these activities.
- 6) I can connect Raspberry Pico to a PC and code simple Python programs to control the Pico board.
- 7) I can connect external circuits on breadboard and use Raspberry Pi Pico with Python programming to interact with external circuits.
- 8) I can understand the analogue-to-digital and pulse-width modulation functions of Raspberry Pi Pico and use both to enable (quasi-)analogue input and output.
- 9) The laboratory activity met my expectations.
- 10) The asynchronous instructions and materials provided enabled me to work effectively.
- 11) Regardless of where I was working, I felt engaged with the activity.
- 12) The negative impacts of COVID-19 on my laboratory work were mitigated by the DCS laboratory arrangements.

Question 1 was designed to group students in terms of their diverse learning environments, which facilitates data analyses and can reveal more insights. For Questions 2-12, the students were asked to give a score from 1-5: 1) Strongly Agree; 2) Slightly Agree; 3) ; 4) Neutral; 5) Strong Disagree.

Of the 121 students enrolled in the course, 73 students completed the survey. Of these 73 students, 55 attended all in-person laboratories, 7 attended all online laboratories, and 11 followed a mixed format of online and in-person laboratories. We show an info-graphic with the summary of their responses to the questionnaire in Fig. 7.

In particular, Questions 6, 7, and 8 establish whether students feel they have met the learning criteria of laboratory sessions 1, 2, and 3, respectively. For all three laboratories, 75% or more of the respondents agree that they have met the learning criteria of the laboratory. With the ‘Strongly Agree’ responses standing at 75%, and 60% for the first and second laboratories, respectively. However, only 35% of students responded ‘Strongly Agree’ to meeting the learning objectives of the third laboratory. As mentioned in Section IV there was no way to simulate the PWM function of Raspberry Pi Pico by the online simulator. Thus, we omit the responses from all but the in-person students for this question. However, even when omitting responses from all but the in-person students, the number who ‘Strongly Agree’ only rises to 37%. This result indicates that the third laboratory might need to be refined or simplified for the next academic year.

When looking at the summary of all responses, we find that more than 60% of students ‘Strongly Agree’ that their learning is well supported (Q2) and that they have been provided clear guidelines (Q3) and instructions (Q11) for the tasks and felt engaged with the laboratory activities (Q10). In addition, according to the responses to Q9, the laboratory activity has met most participants’ expectations. If the ‘Slightly Agree’ responses are included, the number of positive responses rises to 89% (Q2), 86% (Q3), 86% (Q9), 88% (Q10), and 82% (Q11).

Collected data also shows that about 50% of students ‘Strongly Agree’ that they can connect between the lecture content and the laboratory tasks (Q4), by the end of the laboratories, they feel confident working in a laboratory (Q5), and feel COVID-19 had been well mitigated for (Q12). Once again, if the ‘Slightly Agree’ responses are included, the number of positive responses rises to 88% (Q4), 84% (Q5), and 74% (Q12).

As our aim is to put in place a framework for parallel laboratory sessions in order to cope with the negative impacts of COVID-19, we also analysed the responses to the questionnaire of those students who attended either online or blended laboratory sessions. The analytical results show that more than 50% of these students ‘Strongly Agree’ that they have been provided clear guidelines (Q3) and feel engaged with the laboratory (Q11). An average of about 35% of students ‘Strongly Agree’ that they were well supported (Q2), able to connect between the lecture content and the laboratory tasks (Q4), and had confidence working in the laboratory (Q5). Their responses also reflect that the laboratory has met their expectations (Q9), and they have been provided clear

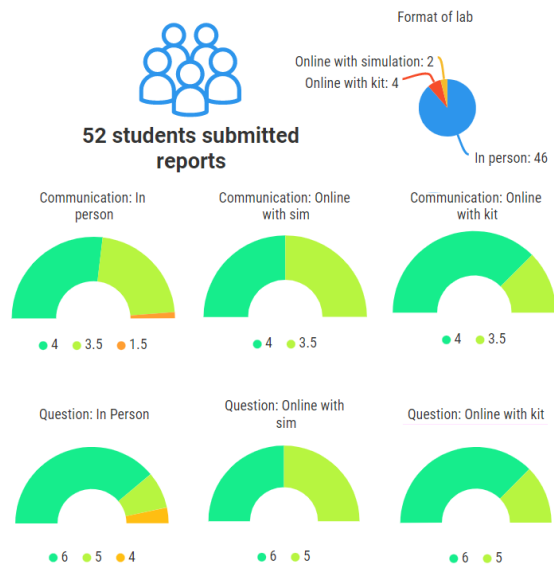


Fig. 8: Results of submitted laboratory reports

instructions (Q10). However, it is worth noting that when the ‘Slightly Agree’ responses are included, the positive responses to all questions rise to approximate 75%. One should note that when isolating the responses of the students who attended the laboratories either completely online or in a blended fashion, 39% of students ‘Strongly Agree’, and 28% of students ‘Slightly Agree’, that the negative impact of COVID-19 on their learning has been mitigated. Only 33% of these students feel ‘Neutral’ about the mitigation put in place, and no online students disagree.

Moreover, no students responded that they ‘Strongly Disagree’ to any questions, and the number that feels they ‘Slightly Disagree’ to any question is a maximum of 3% and an average of 1.25% across Questions 2 to 12. Based on student feedback and the data analyses given above, it is evident that we have successfully put in place a framework for parallel laboratory delivery to cope with the negative impacts of COVID-19. Our students feel positive about the laboratories regardless of the delivery method. Our students also reported feeling supported and engaged with the laboratory content and becoming confident to move into higher-year course units with the acquired skills.

To evaluate the quality of the blended laboratory design on an objective basis, we also examined the reports submitted by students. As this laboratory was formative, not summative, students were not required to submit a laboratory report. Instead students were advised to submit one in order to receive feedback. The laboratory report was assessed in two ways: Communication (4 marks) and technical questions (6 marks). Feedback was then provided to students based off the following criteria:

- Four communication marks:
 - 1 mark for presenting prototype circuit on bread-board or by Wokwi in an appropriate manner.
 - 1 mark for presenting the Python codes in an appropriate manner.

- 1 mark for clear section layout, writing, and typesetting.
- 0.5 mark for adhering to the two A4 page limit.
- 0.5 mark for adhering to the font type and font size requirements (Size 11, Times New Roman).

- Six technical question marks:

- There were six technical questions and students could get a mark for each question answered correctly. These questions are listed in Section III-D.

Unlike attendance at the laboratories, submitting a laboratory report was not compulsory. As such only 52 students submitted laboratory reports for feedback. Of these students, 46 attended in-person laboratories, 4 attended online laboratories but used home kits to complete their report, and 2 attended online laboratories but used simulations to complete their reports. The results of these laboratory reports can be seen in Fig. 8. All online students (using either home kits or simulation) scored 90% or over on the report. Of the in-person students 82.6% scored 90% or over on the report, with 6.5% scoring between 80 - 89%, and 10.9% scoring between 70 - 79%.

In order to rigorously verify the effectiveness of our blended laboratory arrangements and the comparable achievements of intended learning outcomes, we first propose three hypothesis tests of the same nature, i.e., the Student’s t-test, as follows for examining the mean scores of the communication aspect, the technical aspect, and the overall, respectively. Due to the limited number of samples, we choose to combine both online groups with and without home lab kits into one with $N_a = 6$ samples for further assessment against the in-person group with $N_b = 46$ samples. We further denote $X_{a:i}$ and $X_{b:j}$, where $i \in \mathcal{N}_a \doteq [1, 2, \dots, N_a]$ and $j \in \mathcal{N}_b \doteq [1, 2, \dots, N_b]$, as the communication scores awarded to an individual student in both groups, as well as $Y_{a:i}$ and $Y_{b:j}$ as the technical scores in the same configuration. Furthermore, as all students are required to independently conduct the laboratory activities and complete the assessments, we assume that the same types of samples, i.e., $\{X_{a:i}\}_{i \in \mathcal{N}_a}$, $\{X_{b:j}\}_{j \in \mathcal{N}_b}$, $\{Y_{a:i}\}_{i \in \mathcal{N}_a}$, and $\{Y_{b:j}\}_{j \in \mathcal{N}_b}$, are identically and independently distributed (i.i.d.). The overall scores awarded to an individual student in both groups can be written as $Z_{a:i} = X_{a:i} + Y_{a:i}$ and $Z_{b:j} = X_{b:j} + Y_{b:j}$, respectively, which clearly are dependent variables on the scores of communication and technical skills.

To facilitate the following analysis, we make an idealized assumption from the empirical observation that student performance in large classes is likely to be independently Gaussian distributed⁵ [25]:

⁵We are aware that this might not always be Gaussian distributed as reported in [24], while this historical convention can greatly simplify the hypothesis testing process and help to yield insightful statistical inferences. Therefore, we tentatively follow this statistical convention in this paper without investigating the rationality of this empirical observation *per se* in the context of our laboratory teaching. Meanwhile, despite being requested to complete laboratory activities and assessments on an individual basis, students might interact with each other and discuss some assessments, which inevitably compromises the independent attribute of this assumption. As a formative assessment, the available resources and measures we can exercise cannot support a strictly controlled environment for producing completely uncorrelated data samples, and, therefore, this system error needs to be tolerated.

Assumption 1: $X_{a:i}, X_{b:j}, Y_{a:i}, Y_{b:j}$ are Gaussian distributed random variables with means $\mu_a, \mu_b, \eta_a,$ and $\eta_b,$ and standard deviations $\sigma_a, \sigma_b, \delta_a,$ and $\delta_b, \forall i \in \mathcal{N}_a$ and $j \in \mathcal{N}_b,$ which are denoted as $X_{a:i} \sim \mathcal{N}(\mu_a, \sigma_a^2), X_{b:j} \sim \mathcal{N}(\mu_b, \sigma_b^2), Y_{a:i} \sim \mathcal{N}(\eta_a, \delta_a^2),$ and $Y_{b:j} \sim \mathcal{N}(\eta_b, \delta_b^2),$ respectively. All these random variables are mutually independent and most likely to be non-identically distributed.

It is worth noting that, in our statistical setup, we might neither necessarily have $\mu_a = \mu_b$ and $\eta_a = \eta_b,$ nor $\sigma_a = \sigma_b$ and $\delta_a = \delta_b.$ In addition, none of these statistical parameters is assumed to be known, albeit with the knowledge of their unbiased estimates that can be derived from the collected data samples in $\{X_{a:i}\}_{i \in \mathcal{N}_a}, \{X_{b:j}\}_{j \in \mathcal{N}_b}, \{Y_{a:i}\}_{i \in \mathcal{N}_a},$ and $\{Y_{b:j}\}_{j \in \mathcal{N}_b}$ by

$$\begin{cases} \hat{\mu}_a = N_a^{-1} \sum_{i \in \mathcal{N}_a} X_{a:i} \\ \hat{\mu}_b = N_b^{-1} \sum_{j \in \mathcal{N}_b} X_{b:j} \\ \hat{\eta}_a = N_a^{-1} \sum_{i \in \mathcal{N}_a} Y_{a:i} \\ \hat{\eta}_b = N_b^{-1} \sum_{j \in \mathcal{N}_b} Y_{b:j} \end{cases}, \quad (1)$$

and

$$\begin{cases} \hat{\sigma}_a = \sqrt{(N_a - 1)^{-1} \sum_{i \in \mathcal{N}_a} (X_{a:i} - \hat{\mu}_a)^2} \\ \hat{\sigma}_b = \sqrt{(N_b - 1)^{-1} \sum_{j \in \mathcal{N}_b} (X_{b:j} - \hat{\mu}_b)^2} \\ \hat{\delta}_a = \sqrt{(N_a - 1)^{-1} \sum_{i \in \mathcal{N}_a} (Y_{a:i} - \hat{\eta}_a)^2} \\ \hat{\delta}_b = \sqrt{(N_b - 1)^{-1} \sum_{j \in \mathcal{N}_b} (Y_{b:j} - \hat{\eta}_b)^2} \end{cases}. \quad (2)$$

From the above assumption on the score samples, we can apply the basic superposition theorems from probability theory to obtain the lemma infra [26]:

Lemma 1: $Z_{a:i}$ and $Z_{b:j}$ are Gaussian distributed random variables with means $\lambda_a = \mu_a + \eta_a$ and $\lambda_b = \mu_b + \eta_b$ and standard deviations $\nu_a = \sqrt{\sigma_a^2 + \delta_a^2}$ and $\nu_b = \sqrt{\sigma_b^2 + \delta_b^2}, \forall i \in \mathcal{N}_a$ and $j \in \mathcal{N}_b,$ which are denoted as $Z_{a:i} \sim \mathcal{N}(\lambda_a, \nu_a^2)$ and $Z_{b:j} \sim \mathcal{N}(\lambda_b, \nu_b^2),$ respectively. Both $Z_{a:i}$ and $Z_{b:j}$ are mutually independent and most likely to be non-identically distributed.

Proof: See Chapter 6, pp. 181-183, in [26]. ■

As determined in (1) and (2), we can similarly obtain the unbiased estimates of the statistical parameters pertaining to $\{Z_{a:i}\}_{i \in \mathcal{N}_a}$ and $\{Z_{b:j}\}_{j \in \mathcal{N}_b}$ as

$$\begin{cases} \hat{\lambda}_a = N_a^{-1} \sum_{i \in \mathcal{N}_a} Z_{a:i} = \hat{\mu}_a + \hat{\eta}_a \\ \hat{\lambda}_b = N_b^{-1} \sum_{j \in \mathcal{N}_b} Z_{b:j} = \hat{\mu}_b + \hat{\eta}_b \end{cases}, \quad (3)$$

and

$$\begin{cases} \hat{\nu}_a = \sqrt{(N_a - 1)^{-1} \sum_{i \in \mathcal{N}_a} (Z_{a:i} - \hat{\lambda}_a)^2} \\ = \sqrt{\hat{\sigma}_a^2 + \hat{\delta}_a^2 + 2(N_a - 1)^{-1} \sum_{i \in \mathcal{N}_a} (X_{a:i} Y_{a:i} - \hat{\mu}_a \hat{\eta}_a)} \\ \hat{\nu}_b = \sqrt{(N_b - 1)^{-1} \sum_{j \in \mathcal{N}_b} (Z_{b:j} - \hat{\lambda}_b)^2} \\ = \sqrt{\hat{\sigma}_b^2 + \hat{\delta}_b^2 + 2(N_b - 1)^{-1} \sum_{j \in \mathcal{N}_b} (X_{b:j} Y_{b:j} - \hat{\mu}_b \hat{\eta}_b)} \end{cases}. \quad (4)$$

Denoting the significance level as $\alpha,$ the first hypothesis test aiming to examine the equivalence of the achievements of intended learning outcomes related to communication between the online and in-person groups is proposed as follows:

$$H_0 : \mu_a = \mu_b \text{ against } H_1 : \mu_a \neq \mu_b \quad (5)$$

We can construct the following test statistic to assist the hypothesis testing:

$$t_X = (\hat{\mu}_a - \hat{\mu}_b) \left(\Phi_X \sqrt{N_a^{-1} + N_b^{-1}} \right)^{-1} \approx 0.5543, \quad (6)$$

where

$$\Phi_X = \sqrt{\frac{(N_a - 1)\hat{\sigma}_a^2 + (N_b - 1)\hat{\sigma}_b^2}{N_a + N_b - 2}}. \quad (7)$$

In addition, the second hypothesis is established to examine the equivalence of the achievements of intended learning outcomes related to technical skills between the online and in-person groups:

$$H_0 : \eta_a = \eta_b \text{ against } H_1 : \eta_a \neq \eta_b \quad (8)$$

We can similarly construct the following test statistic as (6) to assist the hypothesis testing on the mean of the technical scores:

$$t_Y = (\hat{\eta}_a - \hat{\eta}_b) \left(\Phi_Y \sqrt{N_a^{-1} + N_b^{-1}} \right)^{-1} \approx 0.0484, \quad (9)$$

where

$$\Phi_Y = \sqrt{\frac{(N_a - 1)\hat{\delta}_a^2 + (N_b - 1)\hat{\delta}_b^2}{N_a + N_b - 2}}. \quad (10)$$

Furthermore, we design another hypothesis below to examine the overall performance and achievements of all intended learning outcomes:

$$H_0 : \lambda_a = \lambda_b \text{ against } H_1 : \lambda_a \neq \lambda_b \quad (11)$$

Likewise, we can adopt the same structure of the previous test statistics and propose the following one to assist the hypothesis testing on the mean of the overall scores:

$$t_Z = (\hat{\lambda}_a - \hat{\lambda}_b) \left(\Phi_Z \sqrt{N_a^{-1} + N_b^{-1}} \right)^{-1} \approx 0.3322, \quad (12)$$

where

$$\Phi_Z = \sqrt{\frac{(N_a - 1)\hat{\nu}_a^2 + (N_b - 1)\hat{\nu}_b^2}{N_a + N_b - 2}}. \quad (13)$$

From the rudiments of Student's t-test, it has been proven that $t_X, t_Y,$ and t_Z are identically distributed abiding by the same Student's t-distribution, denoted as $t_X, t_Y, t_Z \sim \mathcal{T}(N_a + N_b - 2)$ [27], which has the quantile (a.k.a. the inverse complementary cumulative distribution function) denoted as $\tau_\alpha(N_a + N_b - 2),$ where α is the significance level, i.e., the tolerable probability of the Type I error, and $N_a + N_b - 2$ represents the degree of freedom. Quantile $\tau_\alpha(N_a + N_b - 2)$ serves as the boundary between the regions of acceptance and rejection of null hypothesis $H_0,$ and the specific values of the quantile with different input arguments can be computed through the method developed in [28]. As a result, the regions of rejection, where null hypothesis H_0 is rejected, with respect to the three hypothesis tests are identical, which can thus be uniformly expressed as⁶

$$|t_{\{\cdot\}}| \geq \tau_{\alpha/2}(N_a + N_b - 2). \quad (14)$$

⁶That is, one should accept the corresponding null hypothesis H_0 on the means of communication, technical, or overall scores iff $|t_{X/Y/Z}| \geq \tau_{\alpha/2}(N_a + N_b - 2).$

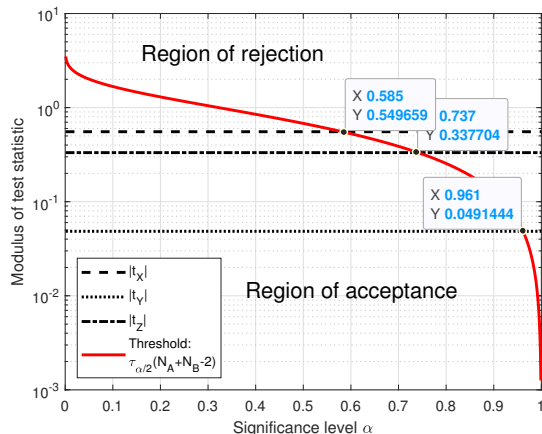


Fig. 9: Test statistics t_X , t_Y , and t_Z derived from (6), (9), and (12), as well as threshold $\tau_{\alpha/2}(N_a + N_b - 2)$ versus significance level α .

Without loss of generality, we plot the test statistics of all three hypothesis tests and threshold $\tau_{\alpha/2}(N_a + N_b - 2)$ versus significance level α in Fig. 9. From the results illustrated in this figure, it is clear that when α is small (this is generally the case for most practical applications in order to prevent Type I errors [29]), we have $|t_X| \ll \tau_{\alpha/2}(N_a + N_b - 2)$, $|t_Y| \ll \tau_{\alpha/2}(N_a + N_b - 2)$, and $|t_Z| \ll \tau_{\alpha/2}(N_a + N_b - 2)$. That is, within a reasonable range of significance level, all null hypotheses H_0 in (5), (8), and (11) are accepted. These test results verify our conjectures about the comparable performance of students attending laboratory sessions online and in person.

In addition, as observed, $t_X > t_Y$ means that the equivalence of students' performance is more significant in terms of the communication aspect than that of the technical aspect. As $t_X > t_Z > t_Y$, it is also in line with our expectation that because $\{Z_{a:i}\}_{i \in N_a}$ and $\{Z_{b:j}\}_{j \in N_b}$ are dependent variables upon $\{X_{a:i}\}_{i \in N_a}$, $\{X_{b:j}\}_{j \in N_b}$, $\{Y_{a:i}\}_{i \in N_a}$, and $\{Y_{b:j}\}_{j \in N_b}$, test statistic $t_Z \approx (t_X + t_Y)/2$ is thereby a compromise between t_X and t_Y .

Jointly considering the robustness of the hypothesis tests, we determine the p-value of Student's t-test statistics based on the symmetry of the Student's t-distribution as follows:

$$\begin{aligned}
 p_{\{ \cdot \}} &= 2 \int_{|t_{\{ \cdot \}}|}^{\infty} h(\theta) d\theta \\
 &= 1 - \frac{2|t_{\{ \cdot \}}| {}_2F_1\left(\frac{1}{2}, \frac{N_a + N_b - 1}{2}; \frac{3}{2}; -\frac{|t_{\{ \cdot \}}|^2}{N_a + N_b - 2}\right) \Gamma\left(\frac{N_a + N_b - 1}{2}\right)}{\sqrt{\pi(N_a + N_b - 2)} \Gamma\left(\frac{N_a + N_b - 2}{2}\right)},
 \end{aligned} \tag{15}$$

where $\Gamma(\cdot)$ is the Gamma function, and ${}_2F_1(\cdot, \cdot; \cdot; \cdot)$ is the ordinary hypergeometric function [30]. Therefore, we can substitute (6), (9), and (12) into (15) to determine the p-values of the three test statistics as

$$\begin{cases} p_X \approx 0.5819 \\ p_Y \approx 0.9616 \\ p_Z \approx 0.7411 \end{cases}, \tag{16}$$

which are aligned with the intersections between the black lines of test statistics and the red curve of the threshold and

suggest the strong robustness of our statistical inferences. When $\alpha \leq 0.2$, which is adopted by most practical applications, we have $p_X > \alpha$, $p_Y > \alpha$, and $p_Z > \alpha$, signifying that all null hypotheses H_0 are inferred to be true with high confidence, leading to the robust equivalence of students' performance resulted from online and in-person laboratory teaching methods. Interestingly, we notice that $p_Z \approx (p_X + p_Y)/2$, which is similar to $t_Z \approx (t_X + t_Y)/2$, also reflects the dependent relations $Z_{a:i} = X_{a:i} + Y_{a:i}$ and $Z_{b:j} = X_{b:j} + Y_{b:j}$.

The hypothesis test results of the laboratory reports are quite clear and robust: there was no discernible difference between the outcomes of students who attended all in person, all online, or in a mix of the two. The results of both the questionnaire and the statistical inference of laboratory reports show that we have succeeded in our aim to develop a framework for parallel laboratory sessions.

We remind ourselves of the intended learning outcomes that were listed in Section II: Describe the internal and external operation of a simple central processing unit (CPU) at the fetch/execute level, create and debug simple Python programs, and describe the principles of a high-level language, compilation and linking. If we compare these to the results of the questionnaire and of the laboratory reports, we can see that the design and delivery of this laboratory has meant that all students, regardless of whether in-person or online, have achieved their intended learning outcomes.

VI. CONCLUSION

This paper proposed and detailed our blended laboratory design for the first-year undergraduate course unit Digital Circuits and Systems using Raspberry Pi Pico and an online Pico simulator. We aimed to employ this blended framework to mitigate the negative impacts of COVID-19 on-campus teaching. The proposed blended framework enables both in-person and online teaching activities to be delivered in parallel. A questionnaire was designed to evaluate the effectiveness of the blended laboratory design, and the empirical data collected from laboratory participants through submitted laboratory reports allowed us to conduct a rigorous hypothesis test to quantitatively compare the students' performance from in-person and online cohorts. The effectiveness of the proposed blended laboratory design has been well supported, and all intended learning outcomes have been achieved as supported by the analysis of the results of the questionnaire and of the laboratory reports. The relevant tools and learned experience can be applied to any future situation that calls for distance learning involving laboratory-based activities, either by course design choice or due to in-person access restrictions.

ACKNOWLEDGMENT

We thank Mr. Richard Walker and Mr. Enea Colleoni, the Teaching Technicians with University of Bristol, for their technical support and preparatory work for the laboratory.

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