Thesis Report

# Abstract

# Acknowledgements

I would like to thank Dr. Aron Michael for his ongoing assistance and patience throughout this semester. In addition to assisting me with this thesis in the usual way, Dr Michael has provided me with invaluable insight into engineering pedagogy. I look forward to working with Dr Michael next year.

# Introduction

## Context

Remote learning has increased in popularity in recent years. The trend towards remote learning has been driven by a variety of stakeholders, including universities, students and new market entrants seeking to undercut the traditional tertiary education model through offering low-cost alternatives. From the perspective of higher education, remote learning confers significant advantages including cost reduction, greater flexibility, and higher levels of student satisfaction, with the flow on benefits thereof. The COVID-19 Pandemic has greatly accelerated this trend. Government restrictions across the world have prevented in-person class attendance. As a result, universities have been forced to rapidly adapt and transition all classes to an online model.

For many programs, this transition to online learning was relatively unproblematic. The exam proctoring challenge notwithstanding, certain courses were very easily transitioned to a completely online model. Courses and programs that require laboratories, however, found the transition to completely online learning challenging. These courses tend to exist within the academic domains of Science, Medicine, Design and Engineering.

The term ‘Laboratory’ has multiple meanings. The term primarily denotes the physical space where researchers conduct experiments, and where students perform structured experiments under the supervision of a laboratory demonstrator. Somewhat confusingly, ‘laboratory’ within the context of an undergraduate course is often shorthand for a type of class which involves ‘laboratory experiments’, or a particular ‘laboratory experiment’. For the purposes of this report, we will use the term in this latter sense unless contraindicated.

Engineering laboratories are an essential part of most engineering courses. Laboratories give students the opportunities to apply abstract knowledge in concrete ways, which reinforces core concepts. Laboratories encourage students to ‘learn by doing’, through trial and error and experimentation. Often knowledge obtained through trial and error is better retained and assists in the development of intuition which complements the structured analytical skills developed in the more theoretical aspects of a particular course. Engineering design also occurs within the context of laboratories.

Within electronics courses specifically, laboratories challenge students to build working circuits. Students are required to learn how to operate equipment like power supplies, signal generators and oscilloscopes. Laboratories, often by design, reveal the limitations of idealised component models. Laboratories transition from highly structured

The LabVIEW framework, as it exists at the time of writing, as implemented by UNSW, presents students with a schematic, which interacts with a physical circuit via switches and relays. Students then take measurements of the physical circuit via an oscilloscope. Although circuit design, even in the form of a breadboard representation, is no substitute for real-world circuit implementation, it is unacceptable that the current solution incorporates no element of actual circuit construction. This is somewhat mitigated by the requirement, in latter electronics courses, that students construct the circuit using Pspice before conducting the physical experiment. Pspice, however, is a design and simulation tool. The aspects of Pspice that make it useful from the perspective of design are the precise things which limit its usefulness in the context of laboratories. Pspice allows for arbitrary measurements of circuit parameters, and the construction of arbitrary sources.

## Problem Statement

Remote laboratories are an essential part of electronics course design; practical experiments conducted within laboratories provide students with important practical skills and reinforce and make concrete theoretical learning. The transition to online learning has been driven by long-term, secular trends and by the acute impact of COVID-19. Unfortunately, the transition to a fully online model in the context Electronics laboratories has been wrought with challenges. The challenges are the result of several requirements that exist in tension with each other:

1. Circuits must be implemented physically, using real components and tested using real laboratory equipment. Circuit simulation, while useful and necessary in the context of design, is no replacement for physical circuit implementation
2. Precision Laboratory equipment is extremely expensive, and it is infeasible and inequitable to expect students to invest in a university-level lab bench for home use
3. Laboratories must incorporate some aspect of design and ideally physical construction on the part of the student. Simply providing a set of measurements to students and asking them to organise and interpret said information is unlikely to instil within the students the desired skills and knowledge that are the object of practical experiments

Current solutions, particularly the solution used by UNSW in the 3 primary electronics courses, ELEC1111, ELEC2133, ELEC3106, make unacceptable trade-offs between the above requirements. Specifically, the LabVIEW framework removes the essential component of circuit construction and physical implementation. The current electronics lab procedure is not integrated – there exists a conceptual disconnect between prelab circuit simulation and practical experiments, and there are practical difficulties with the status quo from the perspective of lab coordination and marking.

This thesis aims to address the shortcomings in current approaches to remote electronics laboratories, with specific focus on the remote labs as implemented by UNSW.

## Thesis Aims

1. To develop an intuitive web-based interface that enables students to build, validate and simulate basic electronic circuits. The interface should allow the student to build and simulate circuits in either a schematic or breadboard representation.
2. To develop a method for implementing student circuits designed using (1) physically via the existing LabVIEW framework, or with some other framework that can be integrated into the existing prefabricated PCB’s used within the context of ELEC1111, ELEC2133 and ELEC3106 Laboratories
3. To combine the two above objectives into a single platform that can be customised, managed and modified as needed by course coordinators and lab demonstrators

**Reach goals:**

1. To allow students to export their designs in a format compatible with SPICE for further analysis
2. To include in the design a platform that allows lab demonstrators to examine and verify student designs.
3. To make the design sufficiently general such that is can be implemented by other universities with disparate course designs, and used as a general online circuit builder and simulator
4. To allow students to overlay simulated and experimental scope readings in order to compare and contrast theoretical and empirical results.

## Report Content and Scope

In order to achieve the stated aims of this thesis, a literature review will be conducted in order to understand user requirements, and to inform key design decisions. The literature review will broadly aim to address several critical questions relating to Engineering pedagogy, and a critical analysis of existing solutions.

The Preliminary Work chapter of this report will aim to identify important details from the literature review, and identify critical skills and decisions that will need be made in the context of design

The design chapter will set out a high-level design of the intended solution, justifying design decisions with reference to the problem statement and the literature review

Finally, the thesis plan will set out a specific plan for the thesis going forward

A bibliography and appendix will be included after the report conclusion, which will cite all academic literature used in this report

# Literature Review

This literature review will begin by broadly analysing the role of experimentation within the pedagogy of Engineering. The pertinent questions this literature review aims to answer are: Why do we place such emphasis on experimentation within engineering education? What are the broad objectives of laboratories and experiments? How do conventional in-person laboratories achieve these objectives? What is the importance of physicality in these laboratories, and is it in-principle possible to achieve all the benefits of in-person laboratories remotely within the constraints of current technology?

The second aspect of the literature review will examine the state-of-the-art with regards to remote learning. Using the normative criteria established in the previous section, current approaches to remote laboratories will be assessed and scrutinised. Current approaches to remote laboratory learning will also be assessed using design objectives explicated in detail at the beginning of the review; specifically, the cost, reliability, ease-of-use, and adaptability of current approaches. The various approaches will also be assessed in terms of idiosyncratic quirks and features. The aim of this section is to determine if current approaches have shortcomings with respect to normative or design criteria, to identify precisely what the shortcomings are and to determine whether the shortcomings can be overcome in-principle.

## The Pedagogy of Electronics Laboratories

### The Role of Laboratories in Electrical Engineering

It is important to distinguish Engineering training with other forms of education that take place in tertiary institutions. The liberal arts, including history, philosophy, literature, attempt to instil within students knowledge for the sake of knowledge. The liberal arts, which stretches back to antiquity, aim to produce virtuous and rounded students who possess critical faculties and an appreciation for art and literature. There is no direct relationship between a liberal arts education and vocation – indeed, most students who graduate with a liberal arts degree apply very little of their knowledge in their occupational roles. One can make a similar argument about the physical, social and life sciences. Most graduates, apart from those few that go on to work in academia of private research roles, never apply the knowledge they gained in a direct way.

Engineering is a vocational degree. Knowledge is imparted upon students primarily to provide them with the skills relevant to engineering as a profession. Thus, programs, courses, lectures and laboratories are chiefly organised around the aim of producing competent and capable engineers.

1. Theoretical and idealised models are instrumental

### Virtual Labs vs. Remote Labs

Table

Description automatically generatedA subtle yet important distinction must be made between the definition and use of ‘Virtual Labs’ and ‘Remote Labs’. The practical consequence of the distinction between Virtual Labs and ‘Remote Labs’ relates to their use in the context of engineering training. Real Labs, in contrast to ‘Virtual Labs’, are performed on actual plants as opposed to simulated plants. Virtual Labs are useful in particular academic contexts but are limited in certain respects. In particular

## Current Remote-Learning Strategies and Existing Solutions

<https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7004872>

### RedPitaya and “Complete System” solutions

The advent of high speed, low-cost ARM processors and the concomitant rise of low-cost development devices like the Arduino and Raspberry Pi. These devices have become ubiquitous in Electrical Engineering education, particularly in design-oriented courses. Many have identified that these devices could potentially serve as the basis for a complete remote laboratory solution. A “Complete System” solution, if possible, would be the holy grail of remote laboratories. These devices are cheap, extremely configurable and would serve a secondary function of introducing Electrical Engineering students to these ubiquitous devices. Unfortunately, there are theoretical, practical and pedagogical issues that prevent limit the effectiveness of these proposed solutions at this point. This literature review will investigate in depth a proposal based on the RedPitaya system by Garcia-Orellana et al. at (2016) the University of Extremadura, Badajoz, Spain.

#### RedPitaya

The RedPitaya system is an extremely powerful single-board computer that is ‘intended to be alternative for many expensive laboratory measurement and control instrument’. The device consists of two 125MS/s RF input and two 125MS/s RF outputs, with 50 MHz analogue bandwidth and 14 bit ADC and DAC converters. Additionally, the device can run a version on Linux.

#### Remote Laboratory Platform Based on the RedPitaya

Researchers at the University of Extremadura have developed a remote labs working prototype based on the RedPitaya device. The prototype solution is comprised of three basic elements:

**1. Web Interface –** “a file programmed in HTML and JavaScript with jQuery, which the NGINX web server [hosted on the device] sends to the client”

**2. Controller –** “A set of C-Programmed functions which is loaded by the web server when any communication is required [with the FGPA]”

**3. Hardware** – Any IO Function of the RedPitaya that interacts with the laboratory circuit. This can include digital switches, analog output, signal generation via a DAC and analog output, signal capture via an analog input and ADC.

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Description automatically generated

The output functions of the RedPitaya (digital and analog IO pins), allow the circuit to be controlled in order to create an interactive lab experience. This is primarily actioned by the *Experiment Control Module*, which is ‘is responsible for changing the circuit connections or modifying the measurement points.’. Such changes are made via relays. In the pilot experiment, the only change made was to change the position of Channel 2 of the oscilloscope. In principle, the experiment control module could be used to allow students to:

1. Dynamically change circuit parameters via switching, either using relays, MOSFETs or other voltage-controlled devices
2. Dynamically adjust “resistor values” within a certain range using JFET’s in place on resistors and controlling base voltage using an analog output

#### Critical Analysis of the RedPitaya Proposal

The RedPitaya system has several advantages. Firstly, the system is a ‘complete package’. The RedPitaya can act as a signal generator and digital oscilloscope, in addition to actuating changes on circuits via relays and voltage-controlled switches and resistors and hosting a web server which allows for student access from another device. The system is also highly adaptable. Since the device runs Linux, the Red Pitaya device could be arbitrarily adapted to suit the specific requirements of courses and institutions. The device is also cost effective – in principle, the device can replace oscilloscopes and signal generators in laboratory settings. The device, priced at 450eu, is far cheaper than most oscilloscopes used in university settings. The price point introduces the possibility of distributing the device to students for at home use.

Despite these numerous advantages, there are several intrinsic limitations on the Garcia-Orellana et al. proposal, and any such proposal using the RedPitaya device or a similar such device. These limitations fall under the following categories:

1. Hardware limitations
2. Pedagogical Limitations
3. Practical Concerns

##### Hardware Limitations

The RedPitaya device, in the context of the Garcia-Orellana et al. proposal, is intended to act as both a circuit actuator, signal generator and digital oscilloscope. In order to determine whether this proposal can in fact act as a substitute for these devices, a thorough comparison must be made between the RedPitaya system, and the digital oscilloscopes and signal generators used in laboratories.

1. **Sample rate, Signal measurement fidelity and bandwidth**. The sampling rate of the RedPitaya is 125Ms/s with 14 bits of resolution. This is excellent given the price point of the device; however, it lags university-standard signal generators by more than an order of magnitude. The populate Rhode & Schwarz RTM3004 can sample signals at **2.5GS/s**. This will likely be acceptable in low level analog electronics courses, where bandwidth is rarely an issue, however high bandwidth oscilloscopes are often required in practical experiments where the oscilloscope bandwidth is required to be much greater than the device being tested. Notably, in Experiment 1 of UNSW’s ELEC2133, students are required to measure the slew rate of an OPAMP, and the (obviously related) approximate frequency at which the device hits its slew rate given a sinusoidal input. This requires an extremely high sampling rate, ideally 100 samples per period. Given the slew rate relationship Slew rate = 2 π f V, the maximum possible slew rate given the desired sampling rate of 100S/period, maximum sampling rate of 125MS/s is 1.25MHz, or a slew rate of ~8V/us. This is acceptable given the slew rate of 0.5V/us of the LM741 and LM301A.

Of greater concern is the nominal input bandwidth of the RedPitaya, or 50MHz. This is 20x less that the 1GHz bandwidth of the Rhode & Schwarz RTM3004. Bandwidth is not of great concern when measuring sine waves, since attenuation won’t cause distortion. Triangle waves can also be closely approximated by their 7th harmonic. When measuring square and sawtooth waves, however, bandwidth is of great significance, particularly when the square wave frequency is high.

**Fourier Series of a Sawtooth Wave**

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**Fourier Series of a Square Wave**

**Schematic

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**Fourier Series of a Triangle Wave**

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Higher harmonics have a more significant effect on square and sawtooth waveforms (n vs n-squared). The 50MHz bandwidth will cause higher the harmonics of the Square/Sawtooth wave to become attenuated. This will result in distortion of high frequency square and sawtooth waves. Specifically, for square/sawtooth wave frequencies over 100kHz, which can contain at most 250 and 500 harmonics respectively. Triangle waves bear very little distortion after inclusion the 15th harmonic.

**Analog signal output voltage, impedance and bandwidth.** The maximum output voltage of the RedPitaya is 1.8Vpp. This is significantly lower than the 10V pp voltage that most signal generators can supply. The output impedance of the analog pins of the RedPitaya are 50ohms. This is comparable to the output impedance of common signal generators. The effect of this is to limit output current to a maximum of 36mA.In practice, the output current is limited to 16mA. Maximum power transfer occurs with a matched impedance of 50ohms at maximum voltage, 16.2mW. The lower maximum output voltage significantly reduces the maximum power transfer of the RedPitaya in comparison to a signal generator, which can theoretically deliver 500mW if operated at 10Vpp with a matched load. The theoretical bandwidth of 50MHz is decent and comparable to the bandwidth of most signal generators. The device is soft limited to 10MHz, which is typical of most signal generators used in academic settings. For comparison, the GFG-8250A has a 100MHz bandwidth, and can produce signals up to 3MHz. Signal generators will produce slightly more faithful square and sawtooth waves at higher frequencies.

##### Pedagogical Limitations

The Garcia-Orellana et al. (2016) paper failed to discuss the role of practical experiments in engineering pedagogy. As a result, the proposed solution failed to integrate pedagogical understandings into the proposed solution. In particular, the proposal is unsatisfactory in the following ways:

1. **The system, out of the box, fails to incorporate design**. Specifically, the only interaction students have in the ‘pilot experiment’ in the research paper is to change the oscilloscope position using a button, which actuates a relay and consequently changes the two nodes that the oscilloscope channel 2 is placed across. This is not an acceptable level of student involvement, particularly for higher level courses.
2. **The ‘integrated oscilloscope’ bears no resemblance to real oscilloscopes**. This is of significant concern, since digital oscilloscopes are ubiquitous in the engineering profession, and becoming proficient in the use of digital oscilloscopes is one of the key outcomes of engineering laboratories. Students must learn to become proficient in the use of oscilloscopes. This is less of a concern for signal generators and power supplies, which are straightforward to operate. Combined with the technical limitations on signal measurement, the inclusion of a separate digital oscilloscope would vastly improve this

##### Practical Concerns

The configuration of the ‘pilot experiment’ appears highly cumbersome. This would need to be done at scale for an entire laboratory – including breadboard implementation, testing components, debugging and verifying. A much better solution would be to prefabricate breadboards with built-in switches or relays that could interface with the RedPitaya IO pins. Additionally, the fact that the web server is hosted on the device, which is within the university network, presents challenges. An additional webserver would need to be created that can proxy to each individual RedPitaya device. This could potentially be a security vulnerability, and university ICT administrators might not be comfortable with this approach. This also removes the possibility of using the design functionality (which doesn’t exist within the proposal, but could be implemented) outside of the confines of the laboratory.

## General Limitations of existing solutions

Circuit simulation software, including LTSpice and iCircuit, is widely used in professional settings. Proficiency in this software is emphasised in undergraduate programs for precisely this reason, and because circuit simulation can allow students to gain an intuitive, as opposed to purely analytical, understanding of electronics. It must, however, be stressed that these programs exist primarily for design and testing.

# Preliminary Work

## Web-Based Programming Experience

It is clear from the literature review that many remote laboratory solutions incorporate some aspect of web-based programming. Modern web technologies are extremely powerful, and high-performance modern browsers enable developers to run complex programs within the user’s browser window. The web has become increasingly standardised over time, which reduces issues relating to app reliability and compatibility.

### HTML

HTML (Hypertext Markup Language) is ubiquitous on the web and serves as the foundation for any web page served to a client. HTML is a hierarchical ‘markup language’ and can be modified with CSS and JavaScript. CSS adds style to HTML documents, and JavaScript can be used to change HTML within the user’s web browser. HTML documents, JavaScript and CSS are processed by the client web browser and not the web server, which simply serves requests.

### JavaScript

JavaScript is a programming language widely used on the web. JavaScript is included within a HTML document, either explicitly or by reference, and is executed by the client browser. JavaScript can interact with the web page and respond to user actions within a web page. For example, JavaScript could be used to add a line of text to part of the web page after a used clicks a button.

JavaScript can also be used on the command line and to process documents on the server side before sending them to the client, in a similar way to Python or PHP. This is accomplished through NodeJS. NodeJS can even be used to host a webserver using the NodeJS module “express”. NodeJS can also call executables and receive responses via a command line interface.

### jQuery and jQueryUI

jQuery is a JavaScript library that greatly extends the functionality of plain JavaScript. jQuery provides a method for referencing and modifying HTML elements, monitoring user interactions via “handlers” and responding to actions via functions. jQuery UI expands the functionality of jQuery again, by adding a set of useful functions in addition to the standard jQuery functions. These functions are of particular interest because they allow for the monitoring of the user mouse position, and the ability to make elements “draggable”.

### Server Control

Server control refers to the way in which a device processes and serves a web page to a user, including authentication. Server control can be accomplished directly via NodeJS, or by using a web server like NGINX or Apache. This server can sit on the lab computer itself, on a cloud webserver or on a cloud Platform-As-A-Service (PaaS).

Authentication takes place on the server side of the application. There are several authentication schemes common across the web. Careful consideration of the appropriateness and practicality of these schemes is necessary

## Controlling LabVIEW from the command line

LabVIEW is a

### Familiarity with LabVIEW operation, design and control

### Operating the LabVIEW via the CLI

### Integrating CLI operation into the user interface

## Circuit Verification and Simulation

### Student Circuit ‘Correct Solution’ Representation

### Transforming Student Circuits into a SPICE-compatible format

### Running a simulation and presenting results to the student

# Design

# Thesis Plan

# Bibliography

Gustavsson, Ingvar, Kristian Nilsson and Thomas Lagö, ‘On Physical Experiments and Individual Assessment of Laboratory Work in Engineering Education’ in Proceedings of the International Conference on Management of Emergent Digital Ecosystems (ACM, 2009) 506