THE UNIVERSITY OF QUEENSLAND

AUSTRALIA

Virtual Laboratories for Electrical Engineering Students: Student Perspectives and Design Guidelines

Ali Altalbe

Master of Information Technology

A thesis submitted for the degree of Doctor of Philosophy at

The University of Queensland in 2018

School of Information Technology and Electrical Engineering

Abstract

This research is focused on understanding the role of virtual laboratories and physical laboratories, specifically in the context of the electrical engineering discipline. It is important to emphasize that the research is not aimed at replacing physical laboratories as they form an essential part of the education of electrical engineers, but rather to supplement them using virtual laboratories. In the literature, there are different perspectives on the implementations of virtual laboratories. Virtual laboratories can be effective for students, particularly those with limitations, either physical or time-based, who may have difficulties accessing physical laboratories or scheduling laboratory time. Instructors and technical staff may find virtual laboratories useful, but with additional challenges for set-up, maintenance and integration with coursework. At the university level, there may be cost considerations that affect decisions about supplementing and/or replacing physical laboratories with virtual laboratories. Throughout the literature, there are multiple studies that argue the effectiveness of virtual laboratories is equivalent to learning in the physical laboratory. Disadvantages found included insufficient realism, ineffective groupwork capabilities, maintenance of the systems and a lack of appropriate skill set development for real-world situations. Advantages included flexibility for students, more time for experimentation, fewer overcrowded classroom and lower costs than physical laboratories. There were gaps in the literature identified related to virtual laboratory design, such as consideration for learning objectives as defined by the Accreditation Board for Engineering and Technology (ABET).

A mixed method approach was used in the research that included both qualitative and quantitative methods. A detailed literature review was performed, supplemented by multiple surveys of both students and faculty. A virtual laboratory was designed and implemented using the input of the students to better understand what users desire in their virtual laboratory and students provided helpful input to the development and refinement of the virtual laboratory. The results of surveys, along with findings in the literature and findings from developing and implementing a working virtual laboratory were combined to answer four research questions. These questions were:

Research Question 1 *– What is the relative capacity of virtual laboratories versus physical laboratories to enable the desired learning objectives of engineering laboratories, especially those viewed as important by students?* In this research teamwork and learning from failures were identified as the most important learning objectives.

Research Question 2 *– Based on a trial virtual laboratory deployment, which design features of a virtual laboratory are important from student perspectives?* In this research realism, online tools for communicating with tutors and a preference for real-time interaction were identified important design features. A flexible, and easy-to-use interface was also important.

Research Question 3 *– What are the advantages and disadvantages of virtual laboratories as a supplement to physical laboratories compared to serving as a replacement for physical laboratories?* This research found that students used the virtual laboratories to prepare for exams, as well as prepare for classroom exercises. Students indicated the need to use virtual laboratories to prepare for real-world scenarios where more and more, particularly in hazardous situations, remote access is preferred. There was also a contingent of students who did not want to use the virtual laboratory at all.

Research Question 4 *– Given the experiences in this trial deployment as well as insights from other virtual laboratory deployments, what is a useful set of design guidelines for virtual engineering laboratories?* The design guidelines developed in this research are as follows:

- **Design Guideline 1 – Enable sharing of knowledge and real-time feedback.**
- **Design Guideline 2 – Enable options for individualized learning and group scheduling.**
- **Design Guideline 3 – Provide consistent and useful responses to errors.**
- **Design Guideline 4 – Provide access to tutors, preferably in real-time.**
- **Design Guideline 5 – Provide additional online help, in the form of tutorials and/or videos.**
- **Design Guideline 6 – Provide realism in the system.**
- **Design Guideline 7 – Ensure that the virtual laboratory supports learning in the physical laboratory.**
- **Design Guideline 8 - Involve students in the design from the beginning.**
- **Design Guideline 9 – Explicitly consider the desired learning objectives in the virtual laboratory design.**
- **Design Guideline 10 – Provide a user interface that is intuitive, simple and easy to use, as well as easy to learn.**
- **Design Guideline 11 – Provide for speed and reliability of the system.**

This research presents a detailed understanding of the learning objectives, user preferences and uses for virtual laboratories from the perspectives of both students and faculty. In this novel research, design guidelines and a framework for implementation consider the learning objectives and user preferences to help fill the literature gap and provide useful material for future designers.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

I acknowledge that an electronic copy of my thesis must be lodged with the University Library and, subject to the policy and procedures of The University of Queensland, the thesis be made available for research and study in accordance with the Copyright Act 1968 unless a period of embargo has been approved by the Dean of the Graduate School.

I acknowledge that copyright of all material contained in my thesis resides with the copyright holder(s) of that material. Where appropriate I have obtained copyright permission from the copyright holder to reproduce material in this thesis and have sought permission from co-authors for any jointly authored works included in the thesis.

Publications during candidature

1. Altalbe, Ali A., Bergmann, Neil W. and Schulz, Mark F. (2015). Educational Utilities of Virtual Laboratories for Engineering Education. In: Proceedings of 26th Annual Conference of the Australasian Association for Engineering Education AAEE 2015, Geelong, Australia. 6-9 December, 2015.
2. Altalbe, A., Bergmann, N. (2016), 'The Importance of Student Feedback in Development of Virtual Engineering Laboratories', World Academy of Science, Engineering and Technology, International Science Index, Educational and Pedagogical Sciences, 3(1), 1538. (Peer- review)
3. Altalbe, A., Bergmann, N. (2017), 'The Importance of Student and Faculty Feedback in Development of Virtual Engineering Laboratories', 28th Annual Conference of the Australasian Association for Engineering Education AAEE, Sydney, Australia. 10-13 December 2017.

Publications included in this thesis

Altalbe, A., Bergmann, N. (2016), 'The Importance of Student Feedback in Development of Virtual Engineering Laboratories', World Academy of Science, Engineering and Technology, International Science Index, Educational and Pedagogical Sciences, 3(1), 1538. Incorporated as Chapter 4.

Contributor	Statement of contribution
Ali Altalbe (Candidate)	Conception and design (90%) Analysis and interpretation (90%) Drafting and production (80%)
Neil Bergmann	Conception and design (10%) Analysis and interpretation (10%) Drafting and production (20%)

Altalbe, A., Bergmann, N. (2017), 'The Importance of Student and Faculty Feedback in Development of Virtual Engineering Laboratories’, 28th Annual Conference of the Australasian Association for Engineering Education AAEE, Sydney, Australia. 10-13 December 2017. Incorporated as Chapter 5.

Contributor	Statement of contribution
Ali Altalbe (Candidate)	Conception and design (90%) Analysis and interpretation (90%) Drafting and production (80%)
Neil Bergmann	Conception and design (10%) Analysis and interpretation (10%) Drafting and production (20%)

Contributions by others to the thesis

My supervisor, Professor Neil Bergmann provided advice on conceptualisation and development of the framework and experiment design, as well as reviewing and editing the publications and thesis prior to submission.

Statement of parts of the thesis submitted to qualify for the award of another degree

None

Research Involving Human or Animal Subjects

No animal subjects were involved in this research. For the survey and interview research contained in this thesis, application reference numbers EC201516ALT and EC201409ALT were made to the Human Ethics Unit and approved by the ITEE ethics office. A copy of these approvals is contained in Appendix VI.

Acknowledgements

This research project would not have been possible without the support of many people. First and foremost, I would like to put on my record my gratitude to thank Allah, then Prof. Neil Bergmann for his support and encouragement throughout the duration of my thesis. I have been extremely fortunate to have a supervisor who took time out for weekly meetings and responded to my questions and queries so promptly. His input and guidance has helped a great deal in providing clarity and direction to the project.

Also, I would like to thank my Mother and Father for their warm supports, many thanks for my Wife Aisha and my daughter Besan for their patients while I am doing my PhD and for their blessings, understanding and endless love. Furthermore, I would like to express my appreciation to my friends here and my family in Saudi Arabia for their support while I am in Australia.

Thank you to The University of Queensland to give me the opportunity to continue my education in area of information technology.

Thank you everyone.

Financial support

This research was supported by a scholarship provided by the Saudi Arabian Cultural Mission.

Keywords

virtual laboratories, electrical engineering, eLearning, physical laboratories, breadboard simulator

Australian and New Zealand Standard Research Classifications (ANZSRC)

080608, Information Systems Methodologies, 40%

930101 Learner and Learning Achievement, 40%

090601 Electrical and Electronic Engineering, 20%

Fields of Research (FoR) Classification

FoR code: 0806, Information Systems, 80%

FoR code: 1302, Curriculum and Pedagogy, 20%

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ABET - Accreditation Board for Engineering and Technology
AC – Alternating Current
CBT – Computer Based Training
CD – Direct Current
CMS - Content Management System
HEO – Higher Education Organization
HSE – Health, Safety and Environmental
ICT – Information and Communication Technology
LED – Light-emitting Diode
LMS – Learning Management System
MOOC – Massive Open Online Course
OFA – Online Formative Assessment
PL – Physical Laboratory
RL – Remote Laboratory
SET - Student Evaluation of Teaching
SL – Simulation Laboratory
TSE – Total Survey Error
VL – Virtual Laboratory
VR –Virtual Reality
VU – Virtual University

1 Introduction

Like many global industries, post-secondary education has seen a significant evolution over the past half century due to the influence of information technology. Higher education at both undergraduate and postgraduate levels has seen considerable innovation in the means through which teaching is provided. While traditional delivery mechanisms such as lectures, laboratories involving real-world equipment and classroom examinations are still employed to a significant degree in higher education, they are being supplemented or replaced by technology-enhanced means such as online streaming of lectures, timed online examinations and virtual laboratories that provide interactive online environments for conducting simulated experiments.

Such modern digital resources serve as tools for educators to enhance the quality of education whilst catering to the individual learning preferences of students. For instance, through traditional means of teaching, students may be limited geographically to the location of the classroom, whereas streaming of such lectures online frees them from such a restriction. This in turn, allows students to save time, manage their learning around a busy schedule with family and work and minimise commuting. However, location is only one of the many limitations that digital education resources solve. Given the scalability of modern media, educators can provide teaching with reduced effort to large numbers of students. As a result, the fees for education can be lowered since delivery costs per student are reduced. Students can rewind or repeat lectures, whilst accessing other resources on the Internet without losing track of the lectures. The digital domain provides an enhanced delivery of education through visual, audio and information-gathering resources that are difficult to replicate otherwise in a purely non-digital domain.

On the other hand, there are some learning activities which are difficult to effectively replicate in an online environment. Engineering laboratories are one such activity, where on-campus delivery is still the dominant mechanism, and online delivery is in its preliminary stages. This thesis undertakes a deep investigation of the advantages, disadvantages, pathways and obstacles in online, virtual laboratories. In [1], virtual laboratories are described as "essential educational tools which provide students real-simulated experiments that can be conducted at any time, without instructor surveillance or guidance."

The research deliverables discussed in this thesis advance the use of such digital technology through the development of design guidelines aimed at addressing various education-related factors that are currently under-addressed in the literature. While various manifestations of education technology are highly capable from a functional point of view, the design itself must also address factors that are crucial to the learning process.

The technology for advanced Internet-based digital learning (technologies such as 2G-4G Internet speeds, convenient streaming of video, interactive Internet communication tools) has been available for just over a decade and less advanced remote-learning tools such as DVDs, computer-based training and correspondence learning for much longer. While the number of tools available to educators is ever-increasing in the face of the exponentially growing capability of technology [2] and given the variety of advantages offered through online education [3], educational technology adoption in higher education institutions is still limited [4]. The mix of conventional and digital education varies depending on the educational scenarios. For instance, streaming of lectures although common in Massive Online Open Courses (MOOC) is less common in university education where in-person classroom lectures are still the norm [5]. On the other hand, simulators are used quite extensively in university laboratory modules particularly in engineering, but often these are used in classes conducted on university premises as opposed to remotely through the internet. While certain tests and examinations are conducted through timed tests online, the main examinations are still carried out by conventional means to reduce the potential for cheating in examinations. Therefore, the inference that can be made from these observations is that there are advantages to conventional on-campus activities that are currently under-addressed through digital education.

The importance of research in the furthering of digital technology for education cannot be overstated. There are several recent developments that corroborate the perception of increased importance of the matter for stakeholders in education at various levels [6] , [7]. There are not only benefits for students, but also commercial benefits for universities, government bodies and investors alike [6] , [7]. The University of Queensland in 2016, provided 15 MOOC courses online registered to and available via edX [8]. Similarly, University of New South Wales provides a total of 7 courses through the FutureLearn platform [9]. Venture capital investment into digital platforms is equally indicative of the importance of this area. The Andreesen Horowitz VC firm portfolio comprises of 8 digital education start-ups, most notable of these include Udacity, AltSchool and Kno [10]. Currently, distance learning through MOOCs and education through degrees at universities are perceived quite differently by students, with the former being a cheaper alternative to the latter [11], and with university degrees being perceived as more valuable in the job market [12]. However, this distinction is increasingly being blurred through the adoption of virtual and digital resources for university education itself. Thus, research into virtual environments and remote online learning are crucial to the progress pushed for by key stakeholders in education.

1.1 Motivation

In bridging the gap between the current state of higher education and the envisaged future state of education employing a significantly greater level of digital resources, the focus of efforts is rightly placed in the development of virtual environments for dissemination of information (data gathering, e-books, articles, access to online papers), interactive media as alternatives to conventional lecturing (audio, video streaming and recording) and for virtual substitutes for specialised education requirements such as simulation tools and 3D modelling. While considerable progress has been made on all three fronts, there is considerable room for progress on the development of virtual environments to facilitate specialised requirements such as those encountered in engineering education.

More importantly, there are several nuances of the learning process that need to be addressed in the development of such virtual environments for them to be effective. There is a significant body of research on the technological aspects of the development of virtual laboratories. However, there is considerable scope for further research into the considerations behind the design process of virtual environments in improving their effectiveness as tools for learning. This thesis investigates under-addressed aspects of the educational process and contributes to the body of research on the subject by suggesting additional considerations that designers should consider when developing virtual laboratories.

There are three main motivations for this research. Firstly, there is a clearly a gap between the capability of technology in addressing education and its current rate of implementation. Given the potential effectiveness of digital technology, research into improving the effectiveness of virtual environments is of significant value to the field of education. Secondly, conventional face-to-face means of education are often preferred despite the potentially lower cost and better scalability offered by on-line delivery. This is an indication that there are under-addressed aspects of the design of digital tools such as virtual labs that are currently better addressed through conventional means. Thirdly, as will be discussed in Chapter 2, the literature on the subject identifies clear gaps for further research. This is further substantiated through evidence gathered over the course of the research project as discussed in subsequent chapters of the thesis.

1.2 Scope

This thesis primarily addresses design guideline for virtual laboratories based on student feedback from the use of a simulation laboratory tool for an introductory university course in electrical engineering. Each of these terms is explained in more detail below.

Laboratory is a term that can mean many things. This thesis specifically deals with university laboratories for coursework teaching in engineering. "Laboratory" can mean both the physical premises and equipment used for experimentation, and it can mean the set of learning exercises that are carried out in those premises with that equipment. Primarily, in this thesis, laboratory is used to mean the particular set of specialized equipment that is used for a set of experiments, and the location where those experiments are conducted. The term "experiment" will be used for a particular learning activity in that laboratory.

Virtual laboratories are defined in [13] as “computer simulations with typically high visualization and interaction capabilities, aimed to help students perform a given (simulated) scientific or engineering experiment” or more succinctly in [14] as “a laboratory experience without the actual laboratory.”

Virtual laboratories can take three forms. Firstly, virtual laboratories can be based on remote interactions with physical hardware in a remote laboratory. For example, remotely controlled electronic switches could configure a real network of components, and te resulting real currents and voltages could be relayed back to the remote user. In this thesis, these are called **remote** laboratories.

Secondly, the equipment and components in a physical laboratory could be replaced by high-quality computer simulations of the equipment. For a simulated electronic circuit, the user can connect simulated components together and observe the simulated current and voltage outputs. These are called **simulation** laboratories.

Thirdly, the virtual laboratory may add additional calculated information to a simulated or remote laboratory which would not normally be visible in a physical laboratory. For example, in the circuit experiment, every single current, voltage and power value in the circuit could be viewed simultaneously, superimposed on the view of the circuit. This could be in a real, physical laboratory with augmented reality displays used to superimpose the information, or it could be additional computer display in virtual laboratories. Such a laboratory is called a **mixed-reality** laboratory.

In this thesis, one simulation laboratory tool is used to gain insights into the principles that might be applied more generally to the design of different types of virtual laboratories for the investigation of different engineering principles. In particular, this virtual laboratory simulates first year electrical engineering coursework experiments in DC circuit design which are part of the first-year course ENGG1300 at the University of Queensland. In the physical laboratory, components are placed on a circuit breadboard, connected to a power supply and the resulting currents and voltages measured. The tool created in this thesis provides a visually realistic simulation of a breadboard, which also simulates the electrical operation of the constructed circuit. The prototype tool developed to facilitate student feedback is a single-user tool, since substantial additional development resources would be needed for a multi-user tool. However, in both the surveys of students and in the subsequent development of guidelines, the need to support collaboration is considered. This includes both collaboration between groups of learners working together on a problem, and tutor support of learners while doing experiments.

The purpose of this investigation is then to develop a tentative set of guidelines to assist the designers of virtual laboratory tools. Development of such guidelines is a multistage process.

Firstly, it is necessary to investigate the educational objectives of existing engineering laboratories. This is undertaken by reviewing the existing literature to identify a meaningful set of learning objectives for engineering laboratories. At this stage, students are surveyed to understand which of these learning objectives they feel are best served by the existing physical laboratories. This is augmented with theoretical analysis of how well the affordances of virtual laboratories match the desired learning objectives.

Next, the understandings of the capabilities of virtual laboratories to implement effective laboratories are used to influence the design of a prototype virtual laboratory for first year DC circuit experiments. The tool is deployed as an optional aid to be used by students who are also undertaking the ENGG1300 course, and it is also deployed for similar electrical engineering students at an overseas university (in the author's home country, Saudi Arabia).

Both groups of students are surveyed on their impressions of the tool and asked to comment on strengths and weaknesses of the tool, and their preferences compared to physical laboratories. A small group of academic staff are also surveyed about their impressions of this tool, and of virtual laboratories in general.

The inputs from the previous stages, including insights from the review of other researchers' deployments of similar tools are then used to develop a tentative set of design guidelines. The purpose of these guidelines is to encapsulate the learning and experiences gained through the deployment of this tool for this one group of experiments, as well as experiences reported in the broader literature. While there have been many guidelines for how to design computer software, including design of educational software, there has not been any consolidated list of design guidelines published for virtual laboratories, and such a list represents a new and significant contribution to the field.

It is worth mentioning what is **not** in the scope of this thesis or claimed as a significant contribution. The designed tool is a prototype used to give students a practical flavour of virtual laboratories to gain their feedback on their advantages and disadvantages. It is not a mature tool ready for wider deployment. Indeed, use of this prototype tool has identified many enhancements that would be needed for such a tool to be most effective as an adjunct or as a replacement for existing labs. This thesis does not quantitatively explore the relative effectiveness of virtual laboratories versus real laboratories in achieving particular learning outcomes by comparing (for example) exam performance of different groups of students using different laboratory realizations. This thesis does not answer the question of whether virtual laboratories are better or worse than physical laboratories. Instead it addresses the question of what issues need to be considered in virtual laboratory design and expresses these issues in the form of a set of design guidelines.

1.3 Overview

This thesis is organised into the following chapters:

Chapter 2: Literature review: In this chapter, the breadth of literature on the subject over the past 15 years and with emphasis on more recent literature in the last 3 years are discussed. Pros and cons of existing solutions are discussed at length, and in doing so the research gaps are identified which forms the focal point of all the original contribution that follows in subsequent chapters.

Chapter 3: Research Questions and Methodology: The relevance of the research objectives in terms of the research gaps identified in the previous chapter is discussed. A formal description of the research questions is presented for each of the research objectives. The methods pertaining to each research question are discussed, and the research methodology is explained.

Chapter 4: Virtual Laboratory Software Tool: In this chapter, the design of the software tool is discussed including the project design, the project implementation and the functional testing of the simulator. The results from a pre-development survey are included.

Chapter 5: Survey Results: The results of additional surveys are presented with descriptive statistics in both table and graph form. This chapter explores the input of the students and how they impacted the design, as well as the findings in the data.

Chapter 6: Answers to Research Questions: Using the findings from the literature search and survey results, the answers to the research questions are presented.

Chapter 7: Design Guidelines: Using the findings and results, as well as the analyses developed to answer the research questions, design guidelines and a design framework for virtual laboratory development are presented.

Chapter 8: Conclusions and Future Work: The chapter firstly summarises the research project. The research contributions made in terms of each of the research objectives are assessed separately. The original contributions from the thesis are presented, including limitations. The scope for future research and development as possible extensions of this project are discussed.

2 Literature Review

2.1 Background and Scope

This research investigates the topic of virtual laboratories for engineering education and looks at developing a set of design guidelines that can assist in the future design of virtual engineering laboratories.

2.1.1 Scope of the Literature Review

This research starts with three observations, which guide the initial directions of the investigations, and which will form the basis of the research described later in the thesis.

Firstly, the implementation of virtual laboratories often assumes that the purpose of including engineering laboratories (physical or virtual) within engineering education programs is clear. The literature review will show that in fact there is limited exploration of the educational justification for engineering laboratories in general, and that clarifying the purpose of laboratories is a necessary first step in designing virtual laboratories.

Secondly, published examples of virtual laboratories are designed by educators, with limited input from the users of the virtual laboratories (students). The literature review will survey existing deployments to discover the issues that designers find important, and then later the research in this thesis will look at what new investigations might be useful to add student perspectives to the design.

Thirdly, and most significantly, there has been limited research on how one would go about designing a virtual laboratory. By undertaking a detailed literature review of previous examples of virtual laboratories and extracting insights from those previous deployments, previous research can provide the starting point for some guidelines for designing virtual laboratories. In addition to this critical analysis of previous work, specific research in this thesis will add student perspectives to the development of these guidelines.

2.1.2 Organization of the Literature Review

This review aims to survey the breadth of existing work that has been done on virtual laboratories for engineering education. In Section 2.2, an overview of online learning and learning management systems is presented along with types of systems and benefits. In Section 2.3, the concept of laboratories is presented along with their purpose, use in engineering education, and their relationship with collaborative education. The evolution of laboratories is then presented, followed by a discussion on several types of laboratories. Section 2.4 focuses on virtual laboratories, reviewing the characteristics and types of virtual laboratories. The steps required to implement virtual laboratories is presented, followed by a comparison of physical and virtual laboratories. Learning outcomes are then explored as well as research into the methods used to measure the effectiveness of laboratories in general and virtual laboratories in particular.

2.2 Online Learning and Learning Management Systems

Tertiary education has embraced new technologies whenever they emerge. Early correspondence courses allowed remote learners to access written materials and custom designed exercises. The availability of electronics, multimedia communications (recordings, radio, television, movies) provided additional support for remote learners. Computers, especially personal computers, further enhanced educational opportunities by allowing interactive educational programs, or Computer Based Training (CBT). However, the development of the World Wide Web in the 1990’s allowed an explosion in interest in remote, computer-mediated education.

In [15] , the author notes that one of the earliest forms of online learning was computer-based training (CBT). CBT systems in the early stages were mostly text-based programs. By the early 2000s, web-based training had emerged [15]. Developments for Information and Communication Technology (ICT) allowed for computer assisted learning and online learning systems to become more mainstream in higher education organizations (HEOs), allowing for new systems such as Blackboard and Saba to evolve [16].

Educational institutions are providing more resources to students through online learning opportunities [17]. Based on results of an annual survey of university senior managers, the importance of providing online learning opportunities has increased from around 49% in 2002 to over 70% in 2014 [18]. With technology advancements, E-learning has become a viable option for providing learning opportunities to a broader range of students [19]. Computers are more affordable and Internet connectivity speeds have boosted developments in online learning [15].

Online learning resources have become increasingly important for both remote and on-campus students. Learning management systems (LMSs) which provide unified access to learning resources such as lecture notes, recorded lectures, and assessment submission have become common using tools like Moodle and Blackboard [20]. Online systems such as Intelligent Tutoring Systems aim to provide customized personalized feedback to learners with minimal intervention by teachers. Third-party discussion forums such as StackOverflow [21] allow learners to interact with industry practitioners. Learner-driven sites, such as RateMyTeachers [22] allow learners to share solutions to past exams, or to provide feedback on learners' experiences of specific teachers and courses.

Online learning systems can be classified as open-source, proprietary and cloud-based systems [16]. Blackboard Learn is a proprietary system, while Moodle and Sakai are considered open-source systems. Docebo is an example of a cloud-based system. Other popular systems are Desire2Learn and Canvas [20]. Online learning tools for content delivery have steadily expanded over time, however the use of cloud-based systems for performing examinations has been approached cautiously [20]. Online systems are used for activities such as providing course material, discussions and chats, and assigning homework, as well as providing laboratory exercises.

Another way to categorize online learning systems are in terms of their features for communication, interoperability and learning context [23]. First generation online learning systems were not interoperable and provided no communication between teachers and students. Second generation systems provided communication between the teacher and student with some add-in features, and third generation systems, or current systems, are fully interoperable and provide more communication capabilities. Features that are important to the success of online systems include accessibility of the system and high-quality material that is useful, consistent and accurate [17]. Usability of a system, in terms of its interoperability with other computer-based tools is also important [20]. Researchers have also found that an easy-to-use user interface leads to higher intentions to use the systems [23].

Overall, online learning has been found to provide benefits to students [19]. In [20], students found that doing laboratory exercises was more efficient when using an online system. When students have a positive experience with online learning, they tend to continue to use the system and improve their learning outcomes [17]. Online classroom discussion forums have been found to help students learn more about course topics [24]. Low motivation and satisfaction levels have been associated with attrition rates that are higher [18]. In [19], the authors argue that while students are open to innovation, they are not as adept at using the online learning tools as they are their other technology devices, such as smartphones and tablets. They also note that students are only using the most basic functions of online learning systems. One of the biggest benefits for both teachers and students is better and more efficient communication [20]. Another benefit to teachers is better organization of course material. Teachers also have found that scoring laboratory exercises is made easier, however instructors also need to continually review and update the content [17]. Teachers are tasked with finding exercises that already exist or creating new ones and adapting the material to the technology [13].

Skills in developing unanimity, individual accountability, positive group leadership, team support, and clarity of instructions are considered as important requirements for effective online group collaboration [25]. Lack of these positive factors, technology related issues, difficulties in virtual communication (because of the use of only written language), and differences in time zones are factors that hinder online group collaboration [25]. E-Learning, or the use of the internet for education, helps overcome the physical obstacles to cooperative learning. Virtual laboratories based on Cooperative Electronic Forums are particularly effective [26]. If cooperative learning activities are well designed then they can stimulate discovery learning, and at the same time they can develop thinking and reasoning [27].

2.3 Laboratories and Engineering Education

This section describes the purpose of engineering laboratories and how they are used in engineering. By “laboratory” we mean equipment and facilities which allows the experimental use of engineering equipment and processes to provide practical demonstration of how physical systems respond to external stimuli. Typically, such experiments are conducted in a purpose-designed room or space, and this facility is also sometimes referred to as a laboratory. Finally, the experiment itself is sometimes called a laboratory. We will call the experiment a laboratory exercise, and the real or simulated equipment for conducting the experiment is the laboratory.

Laboratory exercises can be conducted individually by students, or the students can work together in groups (often 2 or 3 students) to undertake the experiment. Cooperative learning is an important part of laboratory exercises when work is performed as a group and research on cooperative and collaborative learning is described later. Laboratories have evolved with the introduction of new technologies resulting in both traditional laboratory settings and newer virtual, remote and simulation laboratories. This section also includes a discussion of the evolution of laboratories and the different types of laboratories.

2.3.1 Purpose of Laboratories

Laboratories provide an environment for performing experiments and engaging in tasks or practical work related to the topic of study. Laboratory experiments support learning by reinforcing knowledge of concepts, helping students develop experimental skills including experimental design, data collection, analysis and interpretation of results, as well as helping students develop problem-solving and critical analysis skills [28]. Pedagogical reasons for laboratories include learning analytical concepts, preparing for professional practice and situations that are not ideal, learning the instruments, and developing teamwork skills [29]. Lectures and demonstrations are considered "instructivist" approaches that emphasize the delivery of an explanation while "constructivist" approaches emphasize learning tasks where learners can build their own knowledge [30]. After being presented with a theory or concept, the laboratory provides an opportunity for students to perform tests, or experiments, that enhance their learning allowing for their reconceptualization of the theory or concept. In [30], vicarious learning, or learning through dialogue with other learners and instructors can also benefit learners. Collaboration and dialogue are integral to laboratory environments and improve the effectiveness of learning [31].

The various purposes of laboratory experiments, as perceived by students are described in [32]. They define the purposes of laboratories as allowing students to see how things work in real life, designing and following a flow chart, gaining experience through practice, learning the important aspects of experimental work (such as techniques and report writing), and understanding theory. Skills like cooperation and communication with others, as well as understanding scientists' work styles and how experiments are designed while learning how difficult it is to move from theory to practice, are also important objectives. Conclusions from laboratory experiments appear stronger compared to those drawn in classroom demonstrations of experiments, however in [33], the author indicates that the findings of laboratory experiments are sometimes difficult to transfer out of the laboratory. Instructional laboratories have been quintessential in providing education in undergraduate programs because they help students cope with real-world problems and gain hands-on experience [34].

In the context of laboratory experiments, conceptual understanding implies how much a laboratory activity can help the learners understand and solve problems which relate to the basic concepts of the discipline and apply theoretical knowledge to problems in the "real world" [35]. Different skills are required to be learnt. Students learn how to solve open-ended problems and engage their design skills. Social skills refer to how students learn engineering-related tasks in groups, while professional skills refer to the skills required to practice the profession [36]. Learning during the practical work of laboratory exercises may be physical or mental. Instructors may focus on content of the practical task, on scientific inquiry, or both [37]. Laboratories offer more control; the field offers more realism. Laboratories using newer technologies, and incorporating virtual experiments provide both realism and control. Now that more people interact in the virtual world in their daily lives, the realism of the virtual world, including laboratories, has increased as well [38].

2.3.2 Laboratories in Engineering Education

Engineering is unique in that it is both an objective hard science as well as one that often requires practice-based learning using physical equipment [39]. Examination of students in disciplines pertaining to engineering requires them to demonstrate their ability to correctly use equipment to perform experiments. Engineering is a field that relies on physical experiments [40]. Therefore, a significant part of the curriculum for engineering students involves laboratory sessions requiring physical work with equipment. In [41], the authors explain that engineers who have good design capability have the ability to tolerate ambiguity, take a macro view of the system, possess the flexibility to manage uncertainty, have decision making ability, have developed teamwork skills, and have developed the capability to visualize and communicate design ideas. In [42], the author explains an important goal of technology education is to develop critical thinking. Critical-thinking involves analysis of information, synthesis of information, and assessment of the concepts. The engineering profession is a practical discipline which works on materials, energy, and knowledge for the benefit of humanity. This practical knowledge is reinforced by undertaking experiments in laboratories [35].

Courses that are typically a part of the curriculum in the first year of electrical engineering include network theory, transformers, AC-DC circuits, and electrical power generation and use [43]. Laboratories help students to understand complex structures and circuit designs by means of experiments that allow readings on actual systems and to compare these readings with theoretical models. Hands-on laboratory exercises also improve the quality of teamwork among students when they perform in groups to learn the experiments. It improves the interactivity of the students and increases their interest in the subject of the experiments. The need for laboratory practical exercises in engineering that teach students to acquire skills in real world use of equipment is unquestionable [44].

Engineering laboratories can be for development, research and/or education [35]. Engineering professionals utilize the development laboratory for gathering experimental data for design, development, testing and upgrading products. Research laboratories are utilized for obtaining more information about general concepts. Design or development of specific products is not the primary or immediate objective in educational laboratories. Engineering students use laboratories primarily for educational purposes [39].

2.3.3 Collaborative and Cooperative Learning

While engineering laboratory exercises can certainly be undertaken individually, there has been significant research on the advantages of the cooperative learning that occurs when learners work together in groups, or when they engage with teachers during laboratory exercises. Since providing support for group learning is a significant challenge in virtual laboratories, it is worth exploring the advantages of cooperative learning.

Engineering education, specifically electrical engineering, includes laboratory intensive courses. Experimentation is considered essential in scientific and engineering learning [45]. A laboratory environment is used for experiments and facilitates interactions among the students as well as between teachers and students. This interaction improves the effectiveness of the learning in laboratories. Prior research has shown that cooperative, collaborative, active and problem-based learning are beneficial for learning in laboratories [46].

While performing cooperative learning, work groups need to be well-structured, including responsibility allocation, and timeline for the tasks. The purpose must be clear, the workload should be distributed fairly, and students should be a part of the assessment process [47]. Even the faculty members need to have cooperation amongst themselves to ensure success of cooperative learning [48]. However, idiosyncratic factors, such as styles of learning, students' perception about self, previous experience with laboratory equipment and laboratory work, inter-relationships amongst group members, and teaching style are factors which affect the magnitude of the impact [49].

Laboratory-based coursework plays a vital role in scientific and engineering education. Like many other industries, education is impacted by advances in automation and the Internet, allowing engineering laboratories to be accessed online. Online technologies have improved collaborative learning and student learning experiences [35]. The benefits and challenges of online education have been widely explored but extending online education to laboratories brings extra challenges as well as different benefits.

Generally, the laboratory environment is conducive to facilitating interactions among students as well as between teachers and students. Not all experiments are collaborative in nature, yet interactions help improve the effectiveness of the learning which takes place in the laboratories [31]. Studies have also provided evidence in favor of cooperative, collaborative, active and problem-based learning [18]. The instructional method of active learning can engage students in the learning process. In cooperative learning, cooperative incentives are given importance, while competition is not so relevant. In problem-based learning method, problems are given at the beginning of the teaching process, and they form the context to motivate the students to learn. While problem-based learning may or may not improve students' grades, it has been found that retention, attitudes, critical thinking, and study habits are likely to improve [50].

Cooperative learning has always been a part of engineering education and has even gained popularity compared to the traditional lecture-based classroom methods [18]. Learning, achievement, retention and learning attitudes are positively impacted [49]. Cooperative learning can be defined as a learning process where small groups learn in an instructional-environment so that students can collaborate to improve their own learning as well as other group members' learning. There are three common structures of cooperative learning: informal cooperative learning, formal cooperative learning and base-group cooperative learning [48]. Cooperative learning, when combined with methods such as role play, can serve as educational tools for enhancing student active-learning and communication skills [51]. Research has also highlighted that using active learning in a cooperative environment can help to improve the learning of higher-order skills.

The environment, including the technology and the ecosystem, within which this collaboration takes place, is vital and some environments do not have sufficient realism [35]. Factors that have been found to motivate participants to collaborate include managing the interplays between variables related to cognition, social factors, emotional issues and the context [52]. Apart from asymmetric collaboration, problems associated with organization of the group, absence of common goals amongst participants, differences in commitment levels of students and the differences in quality of contribution by the participants are obstacles hindering effective online collaboration. Further, assessment related issues and communication problems are other negative factors [53] . Students consider factors, such as clear objectives, teamwork, motivation, time management, accountability of students, and feedback of instructors as important for supporting online group work [54].

However, teams which communicate online are not necessarily able to do better than the teams physically present together [55]. Working in a group online is more difficult than working face-to-face in a group [54]. Some students feel frustrated during online collaborative work [53]. Some students do not prefer the group work method and prefer to work alone, and some perceive that giving one grade to the entire group is not fair as all members do not do the same amount of work [56]. The problems commonly associated with online group work include students' opposition, issues related to selecting members in a group, insufficient skills for group-work, presence of students who do not contribute to the team, differences in learning abilities of students, withdrawal of some participants, and concerns about the fairness of assessment [57].

2.3.4 Evolution of Laboratories

Over the past few decades, widespread use of computers and an increase in distance learning over the internet have impacted laboratory education significantly. Concepts such as simulation, automatic acquisition, analysis and presentation of data, and the ability to remotely control equipment have changed the laboratory paradigm [39]. Improved capabilities of desktop computers mean that the use of simulations has been increasing [34]. Studies have highlighted the need of developing remote laboratories which can help to perform laboratory tasks from remote places, as an integrated system into the engineering curriculum.

In [58], the authors claim that the advancement of technology from analog systems to digital systems, from macro size to micro size, from wired systems to wireless systems and other developments have reduced the appeal and relevance of physical laboratories compared to virtual laboratories. Newer concepts of mobile virtual laboratories, where students perform experiments using mobile devices, may ultimately move traditional education from e-Learning to m-Learning [59]. In addition, the financial pressure which universities face have forced them to look towards simulation and remote access laboratory systems as alternatives. While universities aim to leverage the technological advancements, there are voices in favour of providing students with exposure to the real-world environment rather than the simulation world [60]. However, despite a recent increase in popularity, the virtual laboratory is still considered by some as an adjunct to traditional laboratories, and not as a substitute for them [61].

2.3.5 Types of Laboratories

Conventional, face-to-face laboratories are referred to here as **physical laboratories**, and those accessed via the Internet are referred to as **virtual laboratories** [62]. These virtual laboratories include remote access to physical laboratories (**remote laboratories**), or Internet access to simulated laboratories (**simulation laboratories**).

There are also combinations of these laboratory types, such as **mixed-mode laboratories**, which might combine remote access to a physical laboratory, with computer-enhanced visualization of the responses in those labs. For example, in [63] animation is used to provide an exploded view of the inside of mechatronics experimental equipment (an inverted pendulum), where internal sensors in the equipment drive this animation with data streamed in real-time from the equipment [63].

Advances in virtual reality (VR), such as headsets for display and gesture recognition, allow fully immersive experiences which can simulate experimental spaces that are not normally observable. Freina and Oft [64] review recent use of VR in educational settings.

Computer games have evolved from standalone single-user games on a single PC to complex simulated worlds where remote players can interact in a single virtual universe. In the same way, virtual laboratories can not only provide access to remote or simulated equipment, they can also simulate the social experience working in groups of leaners supported by tutors in a single work area. Such collaborative virtual environments are called multi-user virtual environments (MUVEs) [65].

These different laboratory styles – physical and virtual laboratories - have been investigated for their effectiveness in achieving different learning objectives. Physical hands-on laboratories emphasize design skills, whilst the virtual laboratories focus on conceptual understanding and convenience of use [35]. Computer simulations can replace expensive, specialized laboratory equipment and provide visualization, as well as interaction capabilities [13]. However, computer screens cannot always replicate the “look and feel” of many laboratory instruments. Many instructional technologies as well as computerized simulations and models are used in virtual laboratories, which can help to replace many of the physical laboratory activities. Some laboratory experiments can only be done with the learners physically present and some require work in the physical laboratory in addition to the virtual laboratory [24].

One method of performing experiments in the laboratory is to use simulation. Simulation technology can represent complex structures on a computer, or even a mobile device and allows students to access remote laboratories. In [66], the authors present a study on the analysis of using simulations as a replacement to real equipment in undergraduate laboratories. The findings indicate that students were positive about simulations and preferred to use them over real light bulbs and resistors. Students using simulation were better at grasping the topics compared to the students using real equipment. A simulated engineering laboratory can provide laboratory experiments, irrespective of the physical location of the learner [66]. Tablet PCs enhanced student learning by representing complex laboratory programs and assignments and allowed the students to make transition from written form to the digital form of laboratory assignments [67].

In essence, the simulators are based on mathematical models of engineering phenomena [34] , [39]. They execute the relevant equations, and hence can be used for creating laboratory environments. They help in giving a pre-laboratory feel and experience of the experiment. With time, the realism and the flexibility of the models have improved as technology has improved. The feeling of isolation associated with working in simulation laboratories has also been mitigated by making the students work in teams and encouraging evaluation by the students themselves. Students have found that social skills and teamwork skills improved using a simulation laboratory [24]. Simulations can help students test hypotheses, or simply help them learn to use measuring instruments [39].

In the context of control engineering, virtual environments do not allow the students to operate the instruments or use instrument-specific software. Further, some simulations do not replicate the impact of noise and disturbances. The level of general competencies and collaborative learning achieved is considered by some to be less potent than the levels achieved in physical experiments [68].

Remote laboratories are similar to simulation systems as experiments can be designed and executed over the Internet. However, physical equipment is used, and remote laboratories provide real data by accessing hardware through a graphical user interface [13]. The equipment is controlled remotely [60]. Remote laboratories are not just restricted to students of the same university but can be shared between universities. This allows universities to collaborate and setup common shared laboratories, thereby reducing the investment of each university for setting up remote laboratories.

A recent study builds a federation protocol for sharing laboratories amongst universities, thereby creating a whole new set of opportunities for bigger laboratories, and better experiments. Recent work discusses the integration of remote laboratories with Content Management Systems (CMSs) and LMSs [69].

Remote laboratories also can be combined with simulation laboratories in a **mixed-reality approach** [70]. Virtual laboratories can incorporate augmented reality, or a blending of real and virtual components. In [71], web-based information is augmented with 3-dimensional visualizations of teaching material where students can pan and rotate objects to examine how components interact with each other. Laboratories using virtual reality and augmented reality allow for a broader range of experimentation possibilities and can enhance effectivity of learning through increased immersion and interaction with multimedia content [71].

The advantages and disadvantages of these different types of virtual laboratories can now be summarized. Simulation laboratories are typically the easiest to deploy. The major cost is software development, and perhaps a centralized server to implement the simulation if it is complex or requires specialized software licences. The number of users is largely unlimited, especially if the software runs on a client machine. Expensive equipment can be simulated at the same cost as low-cost equipment. Additionally, simulations can display system responses that are not possible in real laboratories, such as radioactive decay rates over centuries being displayed in a few seconds. On the negative side, it is more difficult to incorporate features such as faulty equipment, or noisy measurements that are associated with real experiments.

Remote laboratories most closely mimic the physical laboratory, since real equipment in used. Responses are similar to what would be measure in the laboratory. On the negative side, modifying equipment to operate remotely requires significant expertise, specialized scheduling software is needed to queue student access to the equipment, and scaling up to more users is likely to require a proportional investment in additional equipment and the space to house the equipment. The equipment requires maintenance, replacement and updating.

Mixed-reality simulations which add additional visualisation information to a remote laboratory inherit the requirements of both simulated and virtual laboratories. They require physical equipment at a scale that can service users in a timely fashion, and also require the development of sophisticated software to provide the additional visualization information. On the positive side, they can provide a richer educational experience which combines the benefits of the real physical equipment with the ability to “see” what is happening inside that equipment.

Immersive VR laboratories are still largely at the experimental stage, and the high cost of the user equipment (headsets, etc) means they are currently not suitable for deploying laboratory experiments to remote learners. Instead, they are currently most suitable for on-campus simulation of experiments in virtual worlds.

Given these different requirements, this thesis will use the example of a simulation laboratory to investigate virtual laboratories more generally.

2.3.6 Summary of Laboratories and Engineering Education Literature

Laboratories are an important part of engineering education. As technology has progressed, so have the capabilities of laboratories. Laboratories exist primarily to allow experimentation in a controlled environment, or in a sense, laboratories allow engineers to practice. Collaboration and cooperation are an integral part of the learning process and have been shown to help improve the effectiveness of the learning process. There is concern that online learning may interfere with the collaboration which could then affect learning effectiveness. While academics have defined several different types of laboratories, others have acknowledged that as technology improves, there is a merging of the physical and virtual laboratory environments as well as incorporation of virtual and augmented reality components.

Several of the reviewed papers present information that discuss the concept of physical laboratories incorporating more technology and allowing more online learning opportunities. The importance of cooperative learning activities to engineering education and the effectiveness of cooperative learning activities on student achievement is well-documented. While the literature discusses the online learning and the transition of traditional laboratories, the view of how online learning can appropriately replace or enhance traditional laboratories is not well-documented. More research is needed to understand the impact of transitioning to more online learning activities and the impact on engineering education.

Within an engineering education, laboratories serve a distinct pedagogical purpose. As mentioned earlier, laboratory experiments support learning by reinforcing knowledge and concepts, helping students develop experimental skills including experimental design, data collection, analysis and interpretation of results, as well as helping students develop problem-solving and critical analysis skills Pedagogical reasons for laboratories include learning analytical concepts, preparing for professional practice and situations that are not ideal, learning the instruments, and developing teamwork skills. However, there is limited literature on the specific learning outcomes that are expected from engineering educational laboratories and how these are best achieved. In particular, there has not been an explicit analysis of the strengths and weaknesses of virtual laboratories in achieving these learning outcomes, and one of the aims of this thesis is to investigate this area.

2.4 Virtual Laboratories

Over the past few decades, virtual laboratories have gained popularity. They have assumed supportive or even substitutive roles in the context of physical laboratories [72]. Students feel that computer experiences cannot totally replace the physical laboratory experience completely, but they have acknowledged that computer experiences can play a complementary role [73].

2.4.1 Characteristics of a Virtual Laboratory

The concepts of physical and web-based laboratories have been defined by several scholars. The term physical laboratory refers to the traditional laboratories which are built upon real estate and have physical equipment [72]. In contrast, a virtual laboratory is a laboratory experience without the physical laboratory [14]. Virtual laboratories are programmed systems that can simulate the features and activities of the real experiments that are done inside a real laboratory [74]. Virtual laboratories can be categorized and differentiated based on different characteristics.

2.4.1.1 Presentation

Virtual laboratories use heterogeneous formats that include interactive multimedia objects. These formats include texts, sound, hypertext, images, videos, animations and graphics [72]. The virtual learning environment can be located on internet sites [61], and the students or users can control and work with graphical units representing experimental objects. The experiments are conducted via the internet using input devices such as keyboard and mouse [75]. In a virtual laboratory, experiments are conducted and controlled partially or totally by using computers, simulation and animations, and more recently with the use of mobile devices [76]. The access is local or remote but uses the internet. In such laboratories, experiments are viewed via graphical models of the real experiment. The user can observe the process and the end result through the animations [77]. Virtual Reality Systems (VRSs) support creation of tools which allow students to simulate educational environments on their computers [78].

2.4.1.2 Immersion and Engagement

Various models of virtual laboratories differ in their level of replication of reality [72]. The types and levels of virtual laboratories include software sharing, equipment sharing and remote-control laboratories. In the software sharing type, the local simulation software is shared by the server. It processes commands from clients and reports the results of the experiment. The instrument sharing type involves commands from the users to control the instruments which conduct the experiment. The software helps analyze the results. Here, immersion and engagement are low.

In the remote-control virtual laboratory, the users can control the process of the experiment, however, this requires more real-time interaction between the client and the system [75]. The ability of the virtual laboratory to replicate reality can impact the level of immersion, or sense of "being there" or "sense of presence" for the users of the laboratory [70], [79]. Here, immersion is still relatively low but engagement is enhanced because users understand that they are manipulating physical instruments and components.

Virtual environments that promote a sense of "being there together" allow for a shared realism or co-presence in MUVEs [79]. Virtual Reality Systems (VRSs) support creation of tools which allow students to simulate educational environments on their computers [78]. Such systems can potentially provide much higher immersion and engagement, but to date the development and deployment of such systems are very high. As computer gaming becomes more immersive, the availability and cost of such systems may decrease.

2.4.1.3 Source of Data

Based on the data used for experimentation, virtualizations of experiments can be classified as numerical simulation based, measurement data based, real time data based, remote trigger based, remote control-based and hybrid-based [58]. While numerical simulation is purely theoretical, measurement data-based virtualization provides a real feel of the experiment. It is based on the capability of the system to include various combinations of input parameters to replicate the real experiment environment. Virtualization with real time data uses real experiments on real time basis. The user has no control over the experiment apart from the fact that they gather the data online.

The remote trigger-based virtualization is similar to the real-time based type, but the user has the capability to trigger the start of the experiment. Remote control-based virtualization offers the user more flexibility to trigger and control the experiment. This gives a better feel of the real experiment. This system is costlier to design and may involve physical movement and manipulation of objects [1]. It is difficult to scale-up as only one person can use it at a time. The hybrid-based virtualization aims to incorporate the positive features of all the above-mentioned systems [58].

2.4.1.4 Examples of Virtual Laboratory Environments

The "MIT iLab" system is an open-source software framework which supports online (usually remote) laboratory experiments [80]. It was first developed for batch-mode remote experiments (where the whole experimental configuration is first specified, and then later results are returned), but has been extended to support interactive experiments with the addition of a highly configurable service of the laboratory resource scheduling, a huge and strong data storing system, and capability to support high bandwidth communication systems between the laboratory server and the client.

At the University of Belgrade, Serbia in the School of Electrical Engineering, a Virtual Laboratory for Robotics was developed focusing on the notion of dynamics in industrial robots. Students can modify motors, transmission systems and control parameters using a modern user interface while having flexibility in how feedback is provided [81]. In [81], several other initiatives in developing state-of-the-art virtual laboratories are described, including the TriLab at Loughborough University (UK), the Virtual Electric Machine Laboratory at Firat University (Turkey) and the Virtual Laboratory Environment at the Stevens Institute of Technology (USA). Potkonjak et al [81] present a detailed review of recent virtual laboratory deployments.

The International Federation of Automatic Control (IFAC) has been studying virtual and remote laboratories for over a decade, including a control education remote laboratory [13]. The remote options at the RobUALab include robots, servers for the network and teleoperation, camera, and software for modelling, access control and the robot interface [1]. Some of the earliest work with remote laboratories and robotics was developed at the University of Western Australia along with remote robotics developed in the Mercury Project (industrial robot arm with a camera) and the Telegarden Project [1]. In [82], the authors present a comprehensive review of other similar remote laboratory systems.

2.4.2 Comparing Virtual Laboratories to Physical Laboratories

Findings of an extensive study of physical, simulated and remote laboratories conducted by [62] suggested that many physical laboratories today are mediated by computers, thus making them partially equivalent to simulated and remote laboratories. This observation bridges the gap between physical, simulated and remote laboratories. Their study suggests that experiences and beliefs of students could be determined better by the interfaces' nature than the laboratory technology's objective reality.

Developers create and offer virtual laboratories, and the laboratories are also available on CDs [72]. One of the key affordances of virtual labs is that all user interaction is via the computer interface, and so can be captured and analyzed. Virtual laboratories replicate the environment of physical laboratories and have interactive data collection features to support learning and collaboration. Student's activities can be channelled to measure their performance, and to support their learning. The software can have features for student guidance, support, monitoring, and evaluation [14].

In general, physical laboratories can be costlier compared to virtual laboratories, though the 'realism' of reality is difficult to completely replicate [18] , [13]. Monitoring can be more rigorous in virtual laboratories as students input data in the system, and recordings of their activities are available for the teachers to see. Further, a virtual environment offers more flexibility as far as the adjustment of variables is concerned, for example, one could simulate very high-power circuites that are not possible in a physical lab. Virtual laboratories can help perform those experiments which are dangerous and costly to conduct through traditional methods.

Another key affordance of virtual labs, especially simulation labs, is that the responses that are presented to a user are not restricted to those that are observable in physical labs. In a virtual laboratory it is possible to simulate and visualize variables that are difficult to physically measure in the physical laboratory, such as magnetic fields or the inside of a nucleus, or changes in radioactive decay that occur over long periods. Such observations can improve learning outcomes and understanding and may encourage the students to develop an exploratory approach [18]. Compared to the physical laboratories, virtual laboratories are more flexible and open allowing different experiments with different components to be created easily [81]. There is integration between the theoretical and the practical aspects, the learning is continuous, and the methods of teaching can be varied. The learning is necessarily based on multimedia or similar tools [61].

The infrastructure and maintenance requirements are also different as virtual laboratories need updating of software, while the physical laboratories need physical maintenance [72]. The tangible aspects of experimentation, e.g. the feel and sight of substances, are missing in the simulation environment and it is difficult to practically incorporate all possible scenarios in any virtual laboratory system. Consequently, it is possible that students may encounter something totally different when applying the learnings in the real-world scenarios [14]. Physical laboratories generally require high setup and teardown time [60].

Virtual laboratories can substitute or complement physical laboratories when there is paucity of space, funds or there is some problem in the equipment [72]. Apart from being economical, virtual laboratories offer a safer environment [14]. The experiments can be conducted selectively, thereby channeling students' energies to their areas of interest. The freedom enhances the interest and motivation levels and increases the interaction. The process is relatively less time consuming [75]. Within their limitations, such laboratories are excellent for design and testing, provided users can cope with the level of abstraction. Virtual laboratories help in easier sharing of the laboratory resources amongst various teaching organizations and multiple students can access the equipment simultaneously [81]. Even members of public can gain access to experimental equipment virtually. This can encourage people to pursue studies in science and technology [34].

Virtual laboratories can help disabled students or distance learning students [18]. Students, who need comparatively more flexible or visual learning style, may be able to customize the remote laboratories to be more suitable for their learning process. Even a sense of social presence can be created if the students are aware that others are working in the remote lab [60].

Virtual laboratory environments reduce the need for regularly updating the knowledge of the technical staff handling sophisticated and expensive physical instruments and allow for the possibility of sharing instruments between universities [18]. They help in repetition of experiments several times without involving the technical staff or teaching staff. Importantly, such devices can be brought to theoretical classrooms. Hence, if required, theory and practical experiments can be conducted simultaneously within the classroom [59]. In physical laboratories, time pressure can force students to focus on data gathering rather than understanding the fundamental concepts. This problem is overcome in virtual laboratories, and data sharing is easier [83]. Virtual laboratories require less logistical planning and can help in monitoring of students in classes which are overcrowded. They can help overcome deficiencies in physical infrastructure which may exist due financial and other constraints [84].

There are disadvantages to using virtual laboratories. Using physical equipment helps students develop practical skills e.g. malfunction of equipment and solving such problems [18]. Further, they can get exposure to the experiment design and planning problems faced by scientists, especially in long-term experiments. Measurement errors also need to be experienced. Real life delays and the process of thinking about the next steps in case of failure of the experiment design are all part of the learning process. The tangible aspects help in the development of conceptual knowledge. The choice between virtual and physical experimentation may need to be on a case to case basis [85].

It is pertinent to mention that any comparison between the physical and the virtual laboratories requires that the objectives of the laboratory exercise should be decided first. It is also possible that new methods of testing the hypothesis or experiments for development of a design etc. may be devised which are especially suitable in the simulation environment. This will obviate the need for direct comparison between the effectiveness of physical laboratories and simulation laboratories based on the same experiment [39].

Technology can be considered a means rather than an end. Technological applications in teaching do not mean simply using technology to teach in the traditional method. New methods for teaching the topics can be developed by leveraging the technology [73]. It is also accepted that, whatever the approach or the type of lab, teaching should remain student centered so that the learning objectives are achieved [84]. Pedagogical considerations should always remain paramount [72].

In summary, Table 2-2 provides a comparison of physical and virtual laboratories on the factors of availability, experimentation, cost, user experience and interaction. Virtual laboratories are available at any time and provide a safer environment for experimentation. Physical laboratories can be costly, but also can provide a better user experience. Virtual laboratories can provide a good user experience and allow for performance of the assigned experiments without the need for physical equipment. Of the types of virtual laboratories, simulation laboratories tend to have lower costs than remote laboratories. The personal interaction and experience of using real equipment in a physical laboratory is an advantage over virtual laboratories.

Table 2-1 Comparison of Physical and Virtual Laboratories

Factors	Physical Laboratories	Virtual Laboratories
Availability	Limited in time and space - need sharing	Designed for remote, anytime usage
Experimentations	Limited to experiments that can be conducted safely with available equipment e.g. High- Power laboratories. Limited to physically observable responses.	Provides wider & safer options for out of the box experiments. Ability to simulate entities infeasible in physical laboratory.
Cost	Need to build laboratories and need to be updated with updates in timely manner. High upgrade and maintenance cost.	Considerably lower cost-simulation laboratories Medium cost – remote laboratories
User Experience	Best- Actual feelings of physical equipment and experiments.	Second Best- Quick and easy way to perform experiments without physical equipment.
Interaction	Support teamwork and dealings with real world physical equipment and real outcomes	Idealized data and no interaction with real equipment, more difficult to support teamwork

2.4.3 Implementing a Virtual Laboratory

Like many computer systems, the effectiveness of virtual laboratories depends on the quality of the user experience. This section reviews some of the literature on the requirements that different designers have identified in the implementation of virtual laboratories.

The implementation of a virtual laboratory begins with an understanding of the affordances of laboratories. In [85], educational affordances of laboratories in general include the promotion of conceptual understanding, the development of inquiry skills, the cultivation of an interest in exploring science and the development of teamwork skills. Physical laboratories provide the affordances of trouble-shooting equipment, setting up equipment and observations and tactile feedback. The fact that virtual laboratories mediate access via a web interface provide additional HCI affordances. The authors in [85] note that virtual laboratories provide more flexibility by nature of their ability to adapt reality. For example, confusing information can be removed, time scales can be adjusted, and unobservable phenomena can be explored such as electric voltages and currents at arbitrary points in circuit, chemical reactions and thermodynamics. Time scales can be accelerated or decelerated. User interactions can be logged for later processing by learning analytics programs. Equipment “failures” can be explicitly scheduled or prevented. Experimental conditions can be closely controlled. These affordances provide greater control over the students’ learning experiences.

The development of a virtual laboratory requires an analysis of the required hardware and software infrastructure [13]. For a remote laboratory, the specific equipment must be chosen so that it can be controlled remotely, and the responses to stimuli need to be able to be captured. Software is needed to allow students to design the experimental inputs, schedule their use of the remote equipment and retrieve the results. The user interface should also be able to create an adequate level of realism. The system should allow flexibility in defining experiments to allow creativity and open-ended exploration.

Individual differences amongst students and relative openness of the laboratories are important factors to be considered while designing experiments [46]. An experiment’s complexity may influence or encourage the choice of technology, and synchronous or asynchronous communication can be used based on the requirements. Quality of interface and level of social interaction are important aspects to be considered to meet the student needs [46]. It is important that while designing such laboratories the perceptions of the relevant students should be considered. This is because the perception of realism can be manipulated to improve the effectiveness [60].

The design of online group work and the teaching method should be conducive to improving its effectiveness [54]. Features of the online environment, personal attributes of the learners, and the teaching strategies employed by the instructors impact the learning process [54]. Frustration with working in online groups can lead to situations where members drop out of the interactions [55]. Other important barriers hindering participation of students in online group work include lack of availability of time and students’ preference for reading compared to discussing matters online [86].

The design of virtual laboratories needs to account for different user interface devices, such as PCs or tablets [46]. There are setup and management issues associated with laboratories. For example, the level of access can be different for tutors, students or visitors. The support staff involved in virtual laboratories need to have a proactive attitude towards building knowledge, encouraging students, guiding students, and understanding and responding to their concerns [61].

The programmers of these virtual laboratories need to be highly skilled as there is generally custom development required even with off-the-shelf packages [87]. They should also be familiar with the process and objectives of the experiment, as well as the needs of the student users.

The process of conducting an experiment on the system should be explained in simple terms and be easy to understand [88]. The software needs to have a good interface, should have multi-platform portability, and should offer modularity by allowing development of the program in parts. Further, it should be compatible with the available hardware and should align with the existing code [88]. Debugging and help options are important. Features, such as extendable program libraries, increase the flexibility of the system. Multimedia features are particularly important [58]. However, ease of use of the interface is more important in the context of learning and cognition compared to smoothness of navigation [72]. Modularity and customizability of the system are important, and the virtual laboratories should cater to individual differences in students and their levels. Help features can provide real-time guidance and support [14].

Ideally, a virtual laboratory must include a real-life scenario from which the student can collect data in a realistic environment [88]. This is because, in effect, working with a simulation is like exploring an algorithm which tries to imitate the real world. The discoveries made in the process of experimentation may be those related to the algorithm. One approach makes the system appear to control like a real lab [14]. The laboratory responds with a video of the experiment. Students can remotely control the system, watch the video and gather data at various points in the video. The software collects and presents the data gathered or generated by the students. This is different from the simulation where the data is already fed into the algorithm [14]. Animation techniques, videos, and 3D models help make the system more attractive for the students [61].

Representational fidelity and learner interaction are defined as distinguishing characteristics of 3-D virtual learning environments [79]. Representational fidelity consists of a realistic and smooth display of the environment with consistent object behavior, a user representation, spatial audio and kinesthetic and tactile force feedback. Learner interaction includes embodied actions, verbal and non-verbal communication, environmental control and construction of objects and scripting of object behaviors. Representational fidelity and learner interaction support the creation of a realistic environment.

In [89], student feedback was obtained on attitudes towards computer-based laboratories and experimentation. When students were asked to rate important aspects of laboratories, the authors found teamwork to be the highest rated item by the students. Besides rating teamwork highly, students also felt that having assistance from a supervisor or technician was important. In [90], seven elements for design of a remote laboratory were presented including tailoring instructions to skill level, supporting both linear and non-linear presentation of content, limiting the number of sound-based instructions, displaying content in various forms, including interactive content, limiting the amount of text-based content and providing a useful feedback system.

In summary, the design features identified in the literature that are important for a virtual laboratory revolve around ease-of-use, helpfulness and providing realism. These features are summarized in Table 2-3.

Table 2-2 Design Features Identified in the Literature

Design Feature	***Source***
User interface – quality and ease-of-use	[46], [88], [72]
Realism	[88], [14], [79]
Individualized	[46]
Storage capacity, hardware, software	[13], [88]
Social interaction, Teamwork	[46], [89], [79]
Simple to make experiments	[88]
Multimedia, 3-D features	[58], [61]
Help features	[14], [89]
Qualified technical staff	[61], [87]

2.4.4 Measuring Learning Effectiveness in Online Systems

Learning effectiveness has been defined as "how well individuals have achieved their goals in terms of the knowledge gained from a particular course" [17]. Effective learning is demonstrated by the ability to achieve the required results [91]. A more popular learning approach is called constructivism that supports a concept of learning-by doing as the method for learning and retaining knowledge. Traditional learning design focuses on presenting instructions with predictable outcomes in a more controlled setting while constructivism focuses on presenting instruction that enables the learning process [92].

Student work can be “formative”, where the instructor provides constructive feedback to the student, or “summative”, where feedback to the student consists of only a grade or mark [93]. In [94], the authors note that online formative assessments (OFAs) improve student achievement and learning. When class sizes are large there are administrative and time burdens imposed on the instructor to provide formative feedback, however online submissions can automate the feedback process and provide information to the instructor regarding student submission behavior [93]. Other benefits of online assessment include lower costs, flexibility, improved reliability and instant feedback to the student [95]. Online assessments can be administered interactively, on demand and can be presented to many students simultaneously, however students are required to have the necessary computer literacy to complete the assessments and their level of literacy can impact their scores on online assessments [95]. Common methods for delivery of OFAs include e-portfolios, online web tools (discussion boards, blogs, wikis), multiple-choice tests and the one-minute paper (short reflections or journals).

Online feedback helps students develop self-regulation (management of academic behavior) and results in higher learner satisfaction [94]. In [94], seven principles are noted for good feedback practices including clarifying what constitutes good performance, encouraging dialogue, encouraging positive motivational beliefs and self-esteem, facilitating self-assessment, delivering high quality information to students regarding their learning, providing information to instructors to help shape teaching, and providing information to students that will assist them in achieving their desired performance.

There are many methods presented in the literature for measuring learning effectiveness. In [17], the authors argue that learning effectiveness has typically been measured using student perception and whether learning goals are achieved. In their study, they used student perception and student self-evaluation to assess learning effectiveness. For measuring the effectiveness of remote laboratories, a student perception survey measuring how the remote laboratory efficacy approaches that of a physical laboratory has been used [96]. The authors note that other researchers have found there is a high correlation between learning effectiveness and satisfaction with the laboratory. Other authors are less conceptual, advocating the importance of Moodle quizzes with automated evaluation and correction in an online learning environment [20]. They argue that computer-based assessment does a better job of evaluating the student’s abilities for computer programming. In [97], effectiveness was measured as the student’s ability to completely achieve a task with accuracy. Other measures were error rate, amount of assistance that was needed and the percentage of task completion.

In [92], the author developed an e-learning system for component inspection and circuit-wiring practice for automotive engineering students. The three main components of the training system are introduction, content and achievement, where the achievement section is used to evaluate learning results. Learning effectiveness was evaluated using the web-based practices and answers to questions at the end of each learning section. There were also two tests given that covered the textbook used for the course. The objectives of the learning exercises were for students to be able to explain the skills and demonstrate the skills. A satisfaction questionnaire was also used to evaluate the field of learning material (clear objectives, well-organized, easy to understand programs, and helpful), field of learning environment (easy to use interface, documented procedures, online discussion forum for communication) and field of learning achievement (suitable questions that were well-defined, questions relate to content, test confirms the learning condition of the learner).

Some studies have identified motivation, self-efficacy, ease of use, seniors' support, continuous learning culture, email exchange, training contents and ease of use as contributors to learning effectiveness in a training setting [91]. Other researchers have advocated that course feedback and student perception is sufficient. Constructivists have proposed that student faculty contact, active learning, prompt feedback, high expectations, respect for diverse learning methods, cooperation among students and time on task define effective teaching. In [91], the author combines concepts from earlier models in the literature to present a new model of measuring learning effectiveness in an e-learning environment. Using results from student surveys on learning preferences can be combined with student performance and course statistics to evaluate learning effectiveness.

In [98], the author notes that measuring effectiveness "is not simple." Typical factors impacting teaching effectiveness in a face-to-face learning environment include grading policies, course organization, class size, student abilities, breadth of coverage, type of course, and instructor enthusiasm. There are also environmental factors and the student desire for social engagement. Measuring effectiveness presented by researchers has included perceived learning, satisfaction, performance, participation, and interaction. A version of the Student Evaluation of Teaching (SET) or online surveys are commonly used for students to evaluate the online learning experience in higher education. These tools have some weaknesses as they generally measure the teaching effectiveness and may not capture concepts related to the teacher engaging the students or showing flexibility. Grades are commonly used to measure effectiveness, or pre-post testing.

For online delivery effectiveness, user satisfaction is important and perceived learning and satisfaction has been used to measure study effectiveness for online classes [98]. To create the effectiveness model for online learning, the author includes learning experiences, mentor inspiration (motivating), hindrances (roadblocks), technology (design and usability), facilitator (make student want to continue), interaction participation (social communication with instructor and group). The learning experience consists of the degree of understanding, degree of changes in thinking, behavior, belief or attitude, the degree of appreciation for the value, the level of confidence in the concept, and level of confidence with real-world applications.

In summary, there are multiple ways learning effectiveness is measured, including tests and quizzes, but often student surveys, satisfaction, perception and self-reporting measures are used. Some authors have expanded the traditional thinking about effectiveness to include concepts in the online environment, such as the field of learning concept in [92], that includes ease-of-use of the interface, online discussion forums and quality system documentation. The effectiveness model presented in [98] is a more comprehensive model that also includes the concepts of technology and social communication while incorporating the degree of understanding, as well as broader notions about appreciation for the value of learning and confidence of the student.

2.4.5 Measuring Learning Objectives of Laboratory Systems

The parameters to measure the satisfaction with the virtual laboratory system can include time required for experimentation, feelings of immersion, ease of use, scheduling and access, and clarity of instructions [60]. One way to approach the assessment of performance of laboratories is to view it from the perspective of the objectives of engineering instructional laboratories. Basically, it is a consideration of what the students should be able to do after completion of the curriculum. A comprehensive list of such objectives emerged from discussions in a colloquy organized by the Accreditation Board for Engineering and Technology (ABET) in 2002. The colloquy was comprised of experienced engineering educators who attempted to determine the basic objective or purpose of engineering-instructional laboratories irrespective of how the instruction was delivered. The objectives are elaborated below.

1. The first objective relates to *instrumentation*. It states that after completing the course, the laboratory students should know how to take measurements of quantities using instruments and sensors using the instruments.

2. The second objective pertains to the *theoretical models*. It requires that the students should be able to assess the capabilities and the limitations of the predictive powers of models. The students should be able to evaluate whether the theory explains the practical observations or the data gathered.

3. The third objective relates to *experimentation*. The students should be able to design an experiment, specifying therein the equipment and processes. They should be able to conduct the experiment to gather data and interpret it to achieve the objectives of the experiment.

4. The fourth objective relates to *analysis of data*. The students should be able to draw conclusions and substantiate those conclusions. They should also be able to make judgments about the order of magnitude, use the units, and the conversion systems and methods.

5. The fifth objective assesses whether the students can *design* a product or a system. They should know how to use methods, equipment and materials to create a system or a product as per client requirements, and to test and debug the system or the product.

6. Since *failures* are a part of the learning process, the sixth objective requires that if any student fails then he/she should know how to learn from their failures. The students should be able to identify what went wrong, and where? They should be able to re-design or develop the product based on what they may have learnt from the mistakes.

7. The seventh objective requires that the students should develop a demonstrated level of *creativity* to solve real-world problems.

8. This objective requires that the students should be able to develop *psychomotor skills* to select, modify and operate the right tools and resources for completion of the tasks.

9. The ninth objective relates to identification of *HSE (health, safety and environmental) concerns* emanating from the experimentation, the design and the development processes, and address those concerns appropriately.

10. The tenth objective pertains to development of verbal and written *communication* abilities of the student. Depending upon the level and the requirement, the student should be able to generate documents and reports which convey the message to the intended audience.

11. The eleventh objective requires that the students should be able to develop *teamwork skills* so that the duties and responsibilities can be clearly defined, and the objectives of the experiment can be achieved.
12. The twelfth objective relates to *ethical aspects* of working in a laboratory. This requires that students should inculcate the spirit of proper reporting of data and consider all relevant ethical aspects.
13. The thirteenth objective requires that the student should be able to develop *sensory awareness* to gather data from the real-world about real-world problems.

Student retention and satisfaction surveys can be used as an assessment for motivation. Students' comparative performance in various laboratories settings is considered the most relevant method of judging the efficacy of any laboratory system [39].

According to [99], the assessment of effectiveness of virtual laboratories can be measured in three phases. The pre-lecture assessment assesses the existing knowledge is the first phase. The post-lecture assessment and the pre-laboratory assessment of the learnings during the lecture is the second phase. The post-laboratory assessment of learnings during the laboratory experiment and the recall of the concepts taught during the lecture is the final phase [99].

The factors which are considered while designing online laboratories can be used as parameters for evaluation. For example, the depth and speed of interaction, clarity of objectives clearly, speed of feedback, and speed of access can be considered as some parameters while asking the students to evaluate their experience of working with virtual laboratories. On a broader level, the effectiveness can be judged from the viewpoint of cost, access and satisfaction amongst students and faculty members [100]. In [79], the factors of spatial knowledge representation, experiential learning, engagement, contextual learning and collaborative learning are identified as the expected learning benefits of a virtual learning environment and could be used as parameters for evaluation.

Specifically, in the Australian context, it is important to assess any engineering education system based on the letter and spirit of the accreditation program of Engineers Australia. The assessment of any engineering program for accreditation requires an evaluation of the learning and teaching environment, program's structure and content, and the quality-assurance framework [101]. Also, it is also important to follow the competency standards for professional engineers laid down by

Engineers Australia. The 16 elements of competency laid down in the three Stage 1 competencies are particularly relevant. The three competencies relate to the base of knowledge and skill, ability to apply engineering, professional attributes, and personal attributes. The first category requires that the engineers should have a profound knowledge of the basics, and of the relevant speciality. Elements of the second category of competencies relate to problem solving skills through the engineering knowledge gained. Among other things it requires employment of the design process and executing and managing the engineering projects with systematic approaches. The elements of competency related to personal and professional attributes relate to ethics, communication ability, creativity, appropriate conduct and ability to work in teams [101]. The parameters mentioned in the preceding paragraphs can be used to build a scale for assessment of relative effectiveness of different types of laboratories.

2.4.6 Learning Outcomes in Virtual Laboratories

Many researchers have promoted the use of virtual laboratories as a means of enhancing the effectiveness of laboratory-based learning. In [102], the authors claim that the goal of web-based learning is to further develop and execute the Virtual University (VU) concept. Web-based laboratories help remove the restrictions of time and place in learning and support online engineering education. They offer interactivity amongst learners located at different places [72]. They demonstrate the relation between theoretical concepts and their practical applications and help motivate students [39]. Virtual laboratories help in learning the scientific concepts and remove misconceptions [74]. Apart from the actual conduct of experiments, such laboratories also help to develop the students' ability to analyse and interpret information and data, using modern engineering equipment, designing experiments and solving engineering problems. They enhance the capability of the students to work in groups [60]. Asynchronous and synchronous exchanges are common features, and the interactions help improve motivation, engagement, and facilitate testing.

The steps in the process of virtual laboratory experimentation may broadly include writing a prediction, choosing an experiment to test the prediction, viewing the experiment, collecting data in an interactive environment, conducting the analysis, and, ultimately, accepting or rejecting or amending the hypothesis [14]. The remote experiments can be introduced to the students gradually by preparing them. Firstly, they may be asked to refresh or rejuvenate their understandings of the basic-concepts, experimental equipment and experiment requirements. The system itself has help sections to support the familiarization process. Secondly, instructor supervised experimentation may be conducted with time limitations. In the last stage, the students can conduct the remote laboratory experiments more extensively [60].

In [99], it is argued that students working with virtual laboratories learn as much as they do while learning in theoretical lectures. Simulations can be equally or more effective in supporting the learning process [39]. Apart from providing flexibilities related to time and space, the virtual environment helps enhance student enthusiasm due to collaboration. Virtual laboratories may help simplify complex procedures to facilitate conduct of workshops. Such laboratories offer options for easier assessment of students [77]. Virtual laboratories can help increase adaptability of the students, and the time-consuming parts of the physical laboratories can be replaced by the virtual laboratories without any adverse impact on the learning [102]. Virtual laboratories can be adapted more easily and made simpler by highlighting the relevant features. Virtual investigations can achieve the same level of success as physical investigations in the context of building comprehension of main concepts, operations, and their relations [85].

In [77], the authors report that students consider physical laboratories easier to operate and more satisfying than virtual laboratories. The authors argue that virtual laboratories are more suitable for senior students who already know the basics, however virtual workshops may discourage students from working with real equipment. The curriculum for virtual laboratories should incorporate such assignments and discussions which facilitate collaboration and interaction to help improve the transferable skills of the students [77].

In [35], the authors evaluated the attitudes of students towards their prior and preferences knowledge, experiences on computer usage and simulation software, student's cognitive-style, and acceptance of laboratory exercises in simulation laboratories among electronic and telecommunication engineering students. The result showed positive outcomes using simulation-based laboratories; it showed that different cognitive styles or processes among the students had no effect on their thoughts or attitude towards computerized systems and adoption to simulation laboratories. An alternate study showed that physical and remote laboratories were effective for engineering course students of junior level who were studying mechanical engineering subjects. Their study showed that both the physical and remote laboratories were equal regarding learning laboratory content information, the students learn equally well; the students also had a realistic understanding as well of the advantages of the remote laboratories [35].

A study conducted by [103] revealed that virtual instruments provide students with an opportunity to analyze the instrument in more complete detail down to the circuit schematic level as compared to only the anatomic appearance visible in the physical laboratories. Further, the functional diagram of the instrument is also available to provide a better understanding of how the instrument works. Similarly, an empirical study reveals that students working in simulation-based laboratories tend to spend longer fixation time on the screen focusing on the equipment and experiments [104]; which reflects their deeper cognitive activities related to instruments and equipment.

Virtual laboratories increase the speed of the process of experimentation as they increase the degree of flexibility in design, observation and enable the collection of instant results [105]. Such immediate feedback allows the students to adjust theoretical models and help create an active learning environment to evaluate the error more quickly [106].

Studies suggest that virtual laboratories allow students to focus more on data analysis as compared to traditional laboratories [107]. Primarily this is because the data is automatically collected by the computer freeing the student for greater manipulation and analysis [103]. Similarly, [36] suggest in their literature review that half of their reviewed articles highlighted design skills as a major mission of physical laboratories. Contrary to this, [107] claims that the environment of virtual laboratories allows students to focus more on design as compared to physical laboratories.

The learning outcomes identified in the literature are summarized in the following table. Much of the literature supports the overall theory that learning objectives can be reached in a virtual laboratory, however studies are not available that show the evaluation of virtual laboratories across a comprehensive list of objectives, such as the ABET list.

Table 2-3 Learning Objectives in Virtual Laboratories from the Literature

Learning Objective	*Finding*	*Source*
Learning Concepts	Students learn as well as they do in physical laboratories	[99], [39], [102], [35]
Motivation	Students are more motivated	[39]
Instrumentation	Students can analyze instrument in detail	[103], [104]
Theoretical Models	Relate theoretical to practical	[39], [85], [74]
Experimentation	Virtual laboratories increase the speed of experimentation	[105]
Analysis of Data	Better focus on data analysis	[107], [103]
Design	Better focus on design as compared to physical laboratory	[107]
Learning from Failures	Students can evaluate errors quickly	[106]
Communication	Data sharing is easier in virtual laboratories	[83]
Teamwork	Enhance ability to work in groups	[62], [72]

As seen in the above review, there are considerable suggestions in the literature about what are important issues in the design of virtual laboratories. However, there has not been any published work which attempts to bring all these varied insights together in order to provide a simple set of guidelines that a new designer of a virtual laboratory can use to guide their design. One of the aims of this thesis is to develop such a set of guidelines.

2.5 Summary of Virtual Laboratory Literature

The existing literature provides an understanding of the benefits of using virtual laboratories and important factors for their implementation. There is evidence that virtual laboratories have some disadvantages and are not without complications, but overall, they provide positive experiences for many students and have been shown to enhance collaboration and cooperation in student learning. There are a variety of remote and virtual laboratories that are currently used by various educational institutions that make use of new technologies.

The primary disadvantages of virtual laboratories found in the literature include:

- Students encountering totally different situations when they apply skills in real-world scenarios
- No skill development for handling equipment malfunctions of physical equipment
- Measurement errors need to be experienced as well as real-life delays
- Time zone differences hinder group collaboration
- Some environments have insufficient realism
- Assessment is more difficult
- Students get frustrated with online collaborative work
- May not appeal to all learning styles
- Software updating required
- Skills needed to develop the software

The primary advantages of virtual laboratories include:

- Can be less expensive
- More flexible and open
- Can be shared
- Safer
- Helps with overcrowded classes
- Exercises can be done more efficiently
- Less time spent on calibration, more time spent on experimentation

Determining whether student outcomes in virtual laboratories match learning outcomes in physical laboratories depends on various perspectives. For students that have disabilities or are working, virtual laboratories may be determined to be highly effective due to constraints of certain classifications of students. From an instructor perspective, managing the technology involved with a virtual laboratory, may be more challenging than managing the setting up and maintenance of a physical laboratory. From a university perspective, costs may play an important role in whether virtual laboratories are considered effective. Information in the literature presents some of the different perspectives, but a clear definition of measuring learning outcomes depends on the perspective.

There are many descriptions of virtual and remote laboratories available in the literature that describe the components involved, including hardware and software, but the literature fails to present a detailed analysis of how the affordances of virtual laboratories match the desired learning objectives of engineering laboratories.

Many different virtual laboratory implementations have been reported in the literature, and there have been evaluations of the experiences of students in using these implementations, but there is limited evidence that student perceptions and experiences have been used in the initial design. In [79], the authors note that there is a need to establish best practices and guidelines in the development of virtual laboratories, but currently no such set of design guidelines has been produced.

In the next chapter, these research gaps will be explored in more detail, leading to a set of research questions for the thesis.

3 Research Questions and Methodology

This section reviews the research gaps in the literature, poses the research questions to be evaluated and presents the methodology used to answer the research questions.

3.1 Research Gaps

The previous chapter has demonstrated that there is a considerable literature that explains the design, deployment and evaluation of individual virtual laboratory deployments, or in a few cases, the design and deployment of virtual laboratory frameworks that can support a range of different laboratories.

Individual systems have been evaluated in terms of student learning outcomes and student satisfaction with virtual laboratories. Different researchers have identified different strengths and weaknesses of the individual virtual laboratory deployments. There is limited scope, especially within the confines of a single PhD project, to undertake new research which identifies the quantitative changes in student achievement through using virtual laboratories in comparison to physical laboratories.

However, the literature review has identified some research gaps which can be addressed in the thesis. These gaps are as follows.

Firstly, the existing virtual laboratory deployments do not seem to have been based on a clear set of learning objectives that either the existing physical engineering educational laboratories, or their virtual replacements are meant to achieve. System designs may emphasise one or two possible learning objectives, although these are rarely explicitly stated. There has been some work from a faculty perspective in identifying a set of learning objectives (in the form of the ABET list of objectives in Section 2.4.5). However, there has not been a comprehensive analysis of how well virtual laboratories can achieve these objectives, and there has not been significant investigation of which of these objectives are seen by students as important or relevant. The first research question investigates this research gap.

Continuing the theme of student input to virtual laboratory design, significant examples of student input to the design of virtual laboratories were not found. It is now considered good practice to involve the end users of any IT system in the design process of that system. While there have certainly been studies which ask students about their satisfaction with using virtual laboratory tools, significant research about what features students find important was not found. This research gap will be covered by the second research question.

In almost all the literature, virtual laboratories are proposed as a replacement for physical laboratories. There has been limited examination of what roles virtual laboratories might play as a supplemental learning source, in addition to existing physical laboratories. The exploration of this research gap leads to the third research question.

Finally, and most importantly, there is a lack of a unified set of guidelines that a new designer of a virtual laboratory could consult when starting the design of a virtual laboratory. Individual papers may provide one or two suggestions. There are general design guidelines that one might follow in designing any computer-based tool. Many of the tools that are described in the literature appear to start from a specification that tries to replicate the physical laboratory experience in a virtual laboratory tool, but without any deep examination of which aspects of the laboratory experience are being replicated. Except by undertaking a detailed literature review, as described in the previous chapter, there is little help on where to start the design process. This research gap will be examined in the fourth research question, which draws together material from the other three research questions.

3.2 Research Questions

Overall, the literature related to the learning outcomes using virtual laboratories was very positive. The ability to include students from multiple locations with different backgrounds gives more students the opportunity to participate. Students using virtual laboratories were found to be motivated, learning concepts, designing experiments and analyzing and interpreting data, while learning as much as they might in face-to-face settings. Students found virtual laboratories to be easy to operate. Collaboration was enhanced by working in diverse groups. In the literature, it was pointed out that with new technology, differences between virtual laboratories and physical laboratories are becoming less apparent.

As noted earlier, most evaluations describing how virtual laboratories meet learning objectives are very subjective and lack a clear evaluation framework. The only well-constructed set of laboratory learning objectives that are publicly available seem to be the set of ABET objectives mentioned above.

There is little evidence that even this list is widely used in the design or evaluation of engineering laboratories and its development predates modern virtual laboratories. The evaluation literature is very subjective in this area of virtual laboratories – individual authors tend to argue their own point of view which depends on whether they are looking to promote or refute the use of virtual laboratories. In their review, [62] state "*The debate over different technologies is confounded by the use of different educational objectives as criteria for judging the laboratories: Hands-on advocates emphasize design skills, while remote lab advocates focus on conceptual understanding.*"

It is not enough to simply use faculty input for the design of virtual laboratories even though the learning objectives are typically defined by the faculty. It is also important to consider issues that students feel will impact the ability of the tool to support their learning.

Because technology is changing, and online learning methods are more popular, it is important to revisit the learning objectives, which leads to the first research question:

Research Question 1 (RQ1) – What is the relative capacity of virtual laboratories versus physical laboratories to enable the desired learning objectives of engineering laboratories, especially those viewed as important by students?

Necessary competencies of critical thinking, design, creativity, and the ability to work in teams have been identified as important for engineering accreditation. Other literature discusses different aspects of learning objectives in laboratories and tends to focus on design skills, conceptual understanding, instrumentation and teamwork and it is expected that these learning objectives will be important to both students and faculty.

Realism in the implementation of the virtual laboratory is important. A well-designed user interface with available help allows students to work more comfortably with their assignments. The use of multimedia, videos and animation is important and having proactive technical staff was found to be a central factor in a virtual laboratory success. While the research presents characteristics of virtual laboratory implementations, little information is available that discusses the challenges and complications involved in establishing and maintaining virtual laboratories. There is no existing literature related to using the input of students to design and implement a virtual laboratory. A second weakness in the current literature are few technical guidelines for how to develop effective virtual laboratories. Such guidelines should necessarily be tied to the desired laboratory learning objectives. A second research question will be developed around these technical issues which evaluates what technical capabilities of virtual laboratories are important from the viewpoint of the students that are using the virtual laboratory.

Research Question 2 (RQ2) - Based on a trial virtual laboratory deployment, which design features of a virtual laboratory are important from student perspectives?

It is expected that realism will be a key design feature, as well as an easy-to-use interface and the capability to do groupwork. These are commonly cited features in the literature along with the availability of online assistance.

It is expected that students and faculty will utilize the laboratory to supplement assignments, where the online laboratory can allow additional time for experimentation and understanding of instrumentation.

A key research issue in virtual laboratories is understanding how well virtual laboratories achieve the desired learning outcomes of engineering laboratories in comparison to physical laboratories. Understanding the strengths and weaknesses of physical laboratory and virtual laboratory settings is important. While the literature provided sufficient background on the advantages and disadvantages of virtual laboratories, there was scant literature related to using virtual laboratories in addition to physical laboratories. The third research question revolves around an examination of how virtual laboratories can best be used as a complementary activity to physical laboratories.

Research Question 3 (RQ3) – What are the advantages and disadvantages of virtual laboratories as a supplement to physical laboratories compared to serving as a replacement for physical laboratories?

Different sources in the literature describe different aspects of features included in virtual laboratories, however the existing literature fails to produce a comprehensive list of design guidelines for the implementation of a virtual laboratory that includes input from the users (students). Features such as an easy-to-use interface, realism and multimedia help have been identified, but broader design guidelines have not been constructed to incorporate learning objectives and student input in the context of using virtual laboratories to support physical laboratory use. Each new developer starts from scratch in terms of understanding good design features. Using the findings from the literature and the findings related to the prior research questions, the fourth research question is focused on developing a list of design guidelines for virtual laboratory development.

Research Question 4 (RQ4) – Given the experiences in this trial deployment as well as insights from other virtual laboratory deployments, what is a useful set of design guidelines for virtual engineering laboratories?

The goal of this research is to determine which learning objectives and design considerations are important, and how virtual laboratories can supplement physical laboratories. The goal of this research is not to evaluate differences in learning outcomes between students using the virtual laboratory and students using a physical laboratory, or to measure the extent that the virtual laboratory helps students achieve the learning outcomes. While student perception can be used to measure how students felt about achieving some learning objectives, such as instrumentation, a comparative study of students using/not using the virtual laboratory is outside the scope of this research.

3.3 Methodology

In this research, a mixed methods approach is used that consists of both qualitative and quantitative methods [108]. Firstly, a detailed critical analysis of the available literature is performed using a scoping study approach where a systematic review of existing literature related to virtual and physical laboratories is undertaken. Scoping studies are defined as "a process of summarizing a range of evidence to convey the breadth and depth of a field" and can be used to summarize findings as well as identify literature gaps [109]. Secondly, an experimental approach is employed by developing an example virtual laboratory to better understand the challenges related to the laboratory implementation. Thirdly, survey data are analyzed including the quantitative data and qualitative data. .

One particular physical laboratory and a corresponding virtual laboratory have been chosen to examine the design process for development of a virtual laboratory tool. The first year Electrical Engineering program at University of Queensland includes the course ENGG1300. The course has a significant laboratory component which covers AC, DC and operational-amplifier circuit labs, and the DC circuit laboratory component of the course has been chosen as an example laboratory.

3.3.1 Research Question One (Learning Objectives and Virtual Labs)

Theoretically, learning outcomes serve as a primary input into the design of a virtual laboratory along with the intended use of the virtual laboratory. Based on the learning outcomes, design principles and features, as well as the intended usage, design guidelines can be determined.

The first step in answering RQ1 is to identify the general learning objectives of laboratories. Here I will use the only clear list of such objectives, which is the ABET list described in 2.4.5.

Secondly, the effectiveness of virtual laboratories in being able to achieve these objectives will be investigated. The existing literature on virtual labs will be used to identify particular learning objectives which have been demonstrated in previous studies to be well supported by virtual labs. In addition, there are many of the learning objectives, such as safety and ethics, which have never been explicitly analysed in the existing literature on virtual laboratories. For these objectives, the affordances of virtual laboratories will be analysed in the context of the particular learning objectives to see how easy or difficult it would be for virtual laboratories to achieve these objectives.

Thirdly, as the learners in these laboratory settings, it will be useful to get student input into how well students feel that these objectives are covered by existing physical laboratories. This includes student input into their preferred working style. Many engineering laboratories have learners working in groups, and group work is one of the ABET laboratory learning objectives, so it will be instructive to understand students' preferred working style. This student input will be collated from answers to an on-line survey, the details of which are described below in Section 3.3.5.1. This first survey is called the Pre-Design Survey.

3.3.2 Research Question Two (Important Features of Design Tool)

To better understand the design, deployment and use of a virtual laboratory tool, an important experimental component in this thesis is a virtual laboratory system which replicates the physical laboratory used for ENGG1300 DC circuit theory laboratories.

The existing literature suggests that an important issue for virtual laboratories is the functionality and reliability of the software, and how much it resembles real equipment. Moreover, important features include an intuitive user interface, with high speed, responsiveness, stability, and accuracy. An important aspect in physical laboratories is that students have support and immediate feedback from their tutors.

This research question specifically looks at what design features are important from a student perspective. So on-line surveys of student users will be used to understand their preferences. Firstly, students will be queried about what they believe would be important features of a remotely accessed virtual laboratory tools. The survey questions to gather this data will be part of the same Pre-Design Survey, as described in 3.3.5.1 below. The input from the student survey, plus insights from other tools surveyed in the literature review, will then be used to design the tool.

Then the tool will be made available for students to use for one semester as a supplement to their existing physical laboratory exercises. The first version of the experimental laboratory software (Breadboard Simulator) was deployed and components were installed on University of Queensland servers. In addition, a trusted domain at EAIT was registered for our tool at University of Queensland virtual-laboratories.eait.uq.edu.au.

A second survey will then be conducted to get student feedback on the first prototype of the tool. This is called the Post Deployment Survey. In this second survey, students will be questioned about whether they were satisfied with the tool, as explained in 3.3.5.2 below.

The virtual laboratory tool will then be refined further to include student feedback, and the improved tool will be deployed to a new cohort of students and be available for an entire semester for students to use as an adjunct to their regular physical laboratories. Again, the students will be surveyed about their experience with using the tool, and surveyed about how and when they used the tool. This is called the Post-Production Implementation Survey and is explained in 3.3.5.3 below Additionally, semi-structured interviews with teaching faculty will also be conducted to get their feedback.

Results from the teacher and student feedback and the experimental implementation are combined to highlight the features and preferences of students and teachers in the design of a virtual laboratory. These results will feed into RQ4 which examines relevant guidelines in the development of virtual laboratories and thus contribute to the literature on this subject for future research, design and development of virtual laboratories.

3.3.3 Research Question Three (Supplement versus Replacement)

Since the virtual laboratory tool was deployed as a supplement to existing labs, rather than as a replacement, information in the above three surveys will be used to examine how students prefer to work, and how they use the tool.

This will be combined with analysis from RQ1 about the match between virtual laboratory affordances and desired learning objectives for identifying ways virtual laboratories can effectively supplement the use of physical laboratories.

3.3.4 Research Question Four (Design Guidelines)

The design, deployment, use and evaluation of the prototype virtual laboratory provides valuable input to the development of design guidelines in two ways. Firstly, as the tool developer, the steps undertaken during the design to assist in identifying important issues in the tool design can be critically analysed. Secondly, student feedback on the prototype tool gathered from the usability surveys will provide additional information about what are important design considerations from a student point of view. Additionally, analysis of issues described in the existing literature will identify other important issues. Together, these different sources of information can be critically analysed and important issues translated into an initial set of design guidelines.

3.3.5 Survey Implementations

As indicated above surveys will be conducted before tool design, in response to a rough initial design, and after a full-semester deployment of the improved tool. The general survey details are as follows. The exact questions to be asked will be described in the subsequent chapters regarding the surveys.

In the second semester of 2014, an initial qualitative survey was implemented among the first-year electrical engineering students at the University of Queensland. The survey was exploratory in nature for collecting student input to use in the design of an initial Breadboard simulator. The survey revealed the respondents' feedback and opinion about (a) the relationship between group work and laboratory work; (b) work objectives in laboratories; and (c) the most important features they look for when developing simulation software. Based on the responses, an initial virtual Breadboard simulator (virtual laboratory) for electronic circuits (DC) was developed.

A second survey was done in the second semester of 2015 after the first prototype of software was developed. The questions were both educational and technical; in the survey, the respondents described what they liked and disliked about the Breadboard Simulator so that the tool could be further improved. Students were happy and interested to use the virtual tool in their course and provide input for improvements to the tool.

A third survey was performed at the end of the 1st semester 2016 after students had been exposed to using the simulator to optionally supplement their laboratory coursework. This survey requested input from students who had used the Breadboard Simulator and were familiar with the UQ laboratories. The survey consisted of questions regarding student experience with physical laboratories, the Breadboard Simulator and asked the students to rank the advantages of using the Breadboard Simulator and to rank how the Breadboard Simulator best fit with their personal working style. Additionally, semi-structured interviews were held with teaching staff at the end of semester 1, 2016, to allow faculty input into the project.

3.3.5.1 Pre-Design Survey

The first survey (Semester 2, 2014) consisted of three questions and an open response, to give input to RQ1 and RQ2. The three questions, as input to RQ1, included:

- Ranking the advantages of working in groups (best to least advantage)
- Objectives of working in laboratories (5-point Likert, strongly disagree to strongly agree)
- Ranking preferred working style (most to least preferred)

The open response requested input on the most important features for a web interface software that would allow access to laboratory equipment remotely, as initial input to tool design for RQ2. An open response was provided to allow for the maximum flexibility in response so that student input was not constrained by the questioning. The open responses were grouped into like categories and ranked by distribution of responses using a conventional content analysis approach [110].

3.3.5.2 Post-Implementation Survey

The second survey consisted of questions that were developed using the responses from the initial survey as well as questions derived from the ABET framework. The survey questions were developed to provide a comprehensive framework for evaluating the virtual laboratory tool, the Breadboard Simulator. This survey was conducted after the initial implementation.

The survey consisted of questions related to expertise level, hours of usage and browser type. Additional questions were related to user-friendliness, system crashing or freezing, documentation requirements, advantages of online experiments, capabilities of virtual laboratories, instrumentation capabilities, creativity capabilities, overall reactions, and questions relating to the screen, terminology, learning, system capabilities and usability.

3.3.5.3 Post-Production Implementation Surveys

The Breadboard Simulator was refined and made available to students as additional resources and was posted on Blackboard (LMS) in the first semester of 2016 in a production implementation. The virtual laboratory versions of experiments were available at any time for students in addition to their regularly scheduled physical laboratories. Students could use the laboratory if they missed some of the laboratories in the first DC part of the course, use the tool to do or redo those experiments. If students failed to complete the experiments, they could finish off the incomplete parts, or they could use the laboratory to revise circuit concepts or explore new circuits.

Students could engage with the virtual laboratory software as much or as little as they wished. The students' use of the virtual laboratory was monitored online during the semester and recorded for further investigation like when and how they spent their time spent using the virtual laboratories. The virtual laboratory experiment did not comprise any assessment component of the course as it is entirely optional. Non-participation in the study did not affect the ability of students to take part in the course.

After using the tool, students and faculty were surveyed. The student survey consisted of a list of identical questions on 13 different items for both physical laboratories and the Breadboard Simulator, based on the ABET list of factors for measuring the learning objectives in experimental laboratories. The questions relate to understanding theory, design, experiment, teamwork, safety, analytic abilities, procedure, career, tutors, equipment usage, online learning, and autonomy (5-point Likert, strongly agree to strongly disagree). Additional questions requesting users to rank the advantages of working in groups (best to least advantage) and rank preferred working style (most to least preferred) were included.

The faculty survey allowed faculty to rank the importance of the 13 ABET list of factors. Open response questions were provided regarding which learning objectives could be served by virtual laboratories, suggestions for other learning objectives, advantages and disadvantages of virtual laboratories related to learning objectives, economic and organizational benefits, and assessment.

Scheduled interviews with academic staff and students were conducted to supplement information in the survey and learn more about the issues.

3.3.6 Ethical Considerations

The participants for the main experiment and both surveys comprised of first year Electrical Engineering students at the University of Queensland (especially those enrolled in ENGG1300), as approved by the Ethics Committee at Ethics Committee at School of Information Technology and Electrical Engineering ref: EC201409ALT and EC201516ALT. To fulfil this requirement, it was explained to the participants what the purpose of the research study is and that they may voluntarily approach researchers if they need more information about this project.

It was also explained that all information would kept confidential and anonymous unless mutually agreed otherwise. All records (survey data and data analyses) were kept in password-protected hard drives and servers, or locked filing cabinets and will only be accessible to the project researcher and supervisor. Electronic data was password protected and stored a secure disk drive; any hard copy data was stored in a locked filing cabinet in a designated office at UQ. While the developed simulation laboratory was being evaluated, it was important to ensure that participants were not disadvantaged in terms of their learning experience.

3.4 Survey Design and Statistical Analysis

Surveys are a useful tool in engineering research, particularly where that research is concerned with the relationships between technology and human users of that technology [111]. Often in educational settings, surveys are used to understand the impact of an educational intervention. For example, one could use a survey before and after the deployment of a new educational method (such as a virtual laboratory) to judge whether users feel positively towards that intervention. For such comparative surveys, to meaningfully tell whether changes in user's perceptions of the revised course delivery are due to the intervention, it is necessary to keep all other aspects of the course delivery the same (these unchanged aspects are called control variables) and to only vary the one item under consideration (this is called the independent variable). The outcomes of changing the independent variable (such as use of virtual laboratories) will result in changes to the dependent or response variable (such as student satisfaction). Such surveys are designed around the standard experimental scientific method, which is to apply a stimulus to a system and measure its response.

While the literature review has described in detail some of the claimed benefits of the use of virtual laboratories, it is not the intention of this thesis to undertake such a comparative study of learning outcomes from virtual laboratories. This would require quite a different research design methodology. It would firstly require identification of how to measure learning objectives, perhaps through course assessment results, or through surveys. The demographics of the survey respondents would need to be carefully chosen to match the demographics of the class. Then a second class (perhaps in a subsequent year) would need to be taught using virtual labs (if that was the chosen intervention) keeping all other aspects of the course the same, and a similar cross-section of the class would be chosen and surveyed. Alternately, the class could be divided into two groups – one using the virtual laboratories, and one not – and comparative performance on assessment items and survey results measuring less tangible outcomes could be compared. In a "live" university course, such experimental interventions are possible, but require considerable care to ensure no students are disadvantaged and all the control variables are held constant.

The results from surveys always incorporate some measure of statistical uncertainty, since the survey respondents are a subset of the total population under consideration (such as all first-year electrical engineering students). Statistical techniques are necessary to establish the confidence that changes in performance are due to the intervention and are not just statistical variation. Techniques such as a paired t-test (if the same population is surveyed before and after the intervention) or an unpaired t-test for different groups (one with the intervention, one without) can be used to identify the confidence that a change in performance or perception is due to the intervention. For example, if the average score on a test was 80% in the group with an intervention, and if based on the statistics of the test scores, the 95% confidence interval was 75%-85% on the test scores, this means that if the test was repeated many times, with many different cohorts of the same size, then in 19/20 cases, the average test score would be in this range. If the 95% confidence interval for students without the intervention was 60% to 70% with an average of 65%, then the intervention made a statistically significant difference. If the 95% confidence interval for students without the intervention was 70% to 80% with an average of 75%, then the improved average may just be normal statistical variation. Small improvements in performance due to some intervention are difficult to confirm without very large sample sizes, and careful detail to removing other sources of error.

There are multiple sources of error in survey data, where error refers to uncertainty in the data and the ability to make inferences from the data. As the level of uncertainty increases, the certainty in confidence in the results decreases. Sources of error include errors due to sampling and coverage as well as a lack of response (non-response error) to the survey which distorts the cohort membership. Errors of observation include errors in the design of the survey that can affect the responses, for example biased or unclear questions. In [112], a specification error is defined as measuring an incorrect concept and arises when the survey question differs from the concept that should have been measured and can lead to invalid inferences. Measurement error can result from respondents incorrectly answering questions, ambiguous questions on the survey. There can also be errors in processing of survey data, such as coding, entry and tabulation errors. All of these sources of error make such analyses of educational interventions problematic. To reduce the error in the survey design, several techniques can be used [112]. These techniques seek to minimize the total survey error (TSE) by improving accuracy, credibility, comparability, usability, relevance, accessibility, timeliness, completeness and coherence.

Our research team has neither the expertise nor experience to organize such educational interventions in a way that can definitively evaluate their educational impact, and we do not have access to an existing set of high-quality virtual laboratory tools to deploy such an experiment. This is not intended to be a thesis which establishes (or not) the educational advantages of virtual laboratories in improving learning objectives.

Instead, this project uses surveys in a different way. Surveys are used to gather more general information about the perceptions of students towards virtual labs, as a component of engineering software design. Good software design draws on at least three sources of information that drives such software design. Firstly, there are general principles or design guidelines for software design, such as intuitive interfaces and low cognitive load. Secondly, the intended purpose of the software needs to be understood. Thirdly information should be gathered from the intended users of the software about what is important, and in many cases, this includes using an early mock-up of the software, often with limited functionality.

This thesis looks at these three issues from the viewpoint of virtual laboratories. As shown in the literature review, there is limited discussion about what the desired learning outcomes of engineering laboratories are, and hence limited analysis of how virtual labs can support these. Secondly, there is limited analyses of the needs and wants of student users of such virtual laboratories.

Finally, there is not consensus on design guidelines for virtual labs, or even any published lists of the issues that such guidelines should address.

In this thesis, then, surveys are not used to measure changes in student performance or perception. Instead they are used more informally as inputs to the development of design guidelines for virtual labs. These are what Thiel refers to as usability surveys [111].

Firstly, first year electrical engineering students will be surveyed about their understanding of the learning objectives of (physical) laboratories as input to which learning objectives should be prioritized. At the same time, students are also surveyed about their thoughts on what aspects of a virtual laboratory software tool are likely to be most important to them.

Based on this initial survey, a prototype virtual laboratory tool for electrical circuit design will be developed and made available to students. As is common in modern software design, receiving feedback from a prototype implementation gives much richer feedback than simply asking about preferences for a program that is not yet built. After using the prototype virtual laboratory tool, the first-year electrical engineering students will be again surveyed about the usability of the tool, to understand their impressions of the tool.

Since engineering teachers are key stakeholders, their inputs can also be valuable. Semi-structured interviews will be held with faculty so that their inputs can also be fed into the suggested set of design guidelines.

Several surveys will be created that contain Likert-type questions, open-ended questions and relative rankings of importance. Likert-type questions allow for comparing respondent perception on different aspects of virtual laboratories to neutral responses (responses that display no tendency towards a negative or positive perception). Open-ended questions allow for any response to a given prompt. Some questions are formatted as rankings, that allow respondents to rate a given set of responses in relation to each other.

Likert-type questions are used in the surveys in this research and are different than Likert scale questions [113]. Likert scale questions are generally composed of several (four or more) Likert-type items that can be combined into a composite score or variable in a survey that measure aspects of a consistent concept. Likert-type questions are similar in structure to Likert scale questions, but each question stands alone, and the intention is not to necessarily group the questions into composite variables. Typical analysis techniques for Likert-type questions include descriptive statistics, such as frequencies, median or mode, and the standard deviation to measure the spread of different responses. In [96], a technique is presented for analyzing Likert-type data items in the context of assessing responses from surveys used in the assessment of remote laboratory characteristics. This analysis technique will be used for analyzing the Likert-type questions from the surveys developed in this research.

Of course, even though the surveys in this thesis are not trying to evaluate changes in performance due to experimental interventions, the results still are subject to statistical uncertainty, and it is necessary to give some level of confidence in the results.

Where respondents rank different options, then each response will achieve a certain percentage of the vote as most preferred. Similar to estimating election results from a sub-sample poll, such survey results have some statistical uncertainty, which is normally referred to as margin of error (MOE). The margin of error depends on the Confidence Interval that is required (typical values might be 90%, 95%, 99%), it depends on the sample size, and it depends on the total population size.

Consider a survey where the raw score is a percentage, *p*, of the total that selected a particular response, and the number of survey respondents is *n*. Then margin of error uses a value called z*-value, which in turn depends on the confidence interval, as shown in Table 3-1.

Table 3-1 Margin of Error Confidence Intervals

Confidence Interval (%)	z* score
80	1.28
90	1.645
95	1.96
98	2.33
99	2.58

Then MOE for the percentage score is

$$MOE = z^* \sqrt{\frac{p\,(1-p)}{n}}$$

So, for example, if a response was received from 23% of 100 respondents, for a 90% confidence interval, the MOE would be:

$$MOE = 1.645\sqrt{\frac{0.23 * 0.77}{100}} = 7\%$$

The sample percentage is 23%, and with the margin of error of 7%, it assumed that the response of the whole population lies in the range 16%-29%.

Because of the relative informality of the tests, and the limited resources available running the surveys, the respondents will be self-selected from the cohort of first year electrical engineering students enrolled in the first-year circuit theory course at University of Queensland, ENGG1300. All students in the course will be emailed inviting participation in an on-line survey, and those that elect to participate will answer the survey. No demographic information will be collected, since it is assumed that the students in the class will be relatively uniform in their demographic characteristics, and so the selected sample will be indicative of the entire class. The number of respondents will be used to evaluate the margin of error, as described above. Details of the survey content will be covered in the subsequent chapters, along with the analysis of the results.

4 Pre-Design Survey and Virtual Laboratory Software Tool

In this chapter, the design of a prototype virtual laboratory environment based around a simulation tool is described. In Section 4.1, the results of a pre-design survey of students to identify some key design requirements are presented. Subsequent sections describe the software system design, the detailed simulator interface design, and the testing of the tool.

4.1 Pre-Design Survey

This section describes the design of the survey implemented prior to the development of the simulator tool. This discussion is followed by the results of the closed and open-ended responses from the students and how this information was used in the development of the simulator tool.

4.1.1 Survey Design

An initial survey was conducted to inform the design of the software tool to be implemented as part of RQ2. This survey is used to provide input to RQ1, particularly in gaining insights about which learning objectives are significant from a student point of view. This survey was aimed at gathering insights regarding the students’ preferred working styles, the objectives of working in laboratories and the advantages of working in groups. The initial survey was conducted prior to the implementation of the Breadboard simulator using questions developed in consultation with the course coordinator for ENGG1300.

As listed in the methodology section above, the survey first seeks to provide additional input to the analysis laboratory learning objectives in RQ1. This was done by asking three survey questions.

Firstly, as described earlier, many engineering laboratories use group work, and one laboratory learning objective is teamwork. However, there is less information about student impressions of the usefulness of laboratory group work, so the first questions ask students to rank the following potential advantages of group work (best to least advantage) that were identified from the literature:

- Sharing knowledge
- Better understanding of the subject
- Getting real-time feedback and developing critical thinking
- Looking at concepts from a different perspective
- Supporting creative thinking
- Developing teamwork skills

As described in Section 2.4.5, there is a published list of laboratory learning objectives from a workshop involving engineering faculty, but there is little published information about how students view these objectives, so the second question asks students to evaluate the importance of these objectives. The teaching in staff in this course, ENGG1300, were consulted about which of the learning objectives were addressed by the ENGG1300 laboratory experiments, and four objectives were identified - use of equipment, reinforcing theoretical concepts, critical thinking, and experimental design. For each of these four, students were asked about their agreement with the statement that laboratories helped them to achieve these objectives, with answers given using a 5-point Likert, (strongly disagree to strongly agree).

The third question was designed to evaluate student perspectives of the often-quoted advantage of virtual laboratories that students could undertake learning when and where they want. This question tests this assumption by asking students to rank their preferred working style (most to least preferred):

- On my own during scheduled classes
- In a group during scheduled classes
- On my own during my own time
- In a group during our own time
- Watching a demonstration by the lecturer

The open response requested input on the most important features for a web interface software that would allow access to laboratory equipment remotely, as initial input to tool design for RQ2. The exact survey questions and format are are shown in Appendix I.

All students enrolled in ENGG1300 (around 500) were invited to participate in the survey resulting in 99 completed responses. This give a margin of error for a 90% confidence interval of approximately 4-8% for the percentage values given below.

Of the 99 responses, 77 students provided feedback on the open-ended question related to important features in the software. The purpose of this survey was to garner information from students that could be used in the initial design and was exploratory in nature.

4.1.2 Results from Closed-Ended Responses in the Initial Survey

In Table 4-1, the responses for the highest rated option to the question "*Rank the following advantages of working in groups*" are shown along with the percentages of responses in Figure 4-1.

Table 4-1 Responses to Initial Survey Question 1

Option	**Responses**	**Percentage %**
Sharing knowledge	37	36%
Better understanding of the subject	26	25%
Getting real-time feedback and developing critical thinking	22	21%
Looking at concepts from a different perspective	7	7%
Supporting creative thinking	4	4%
Developing teamwork skills	5	5%

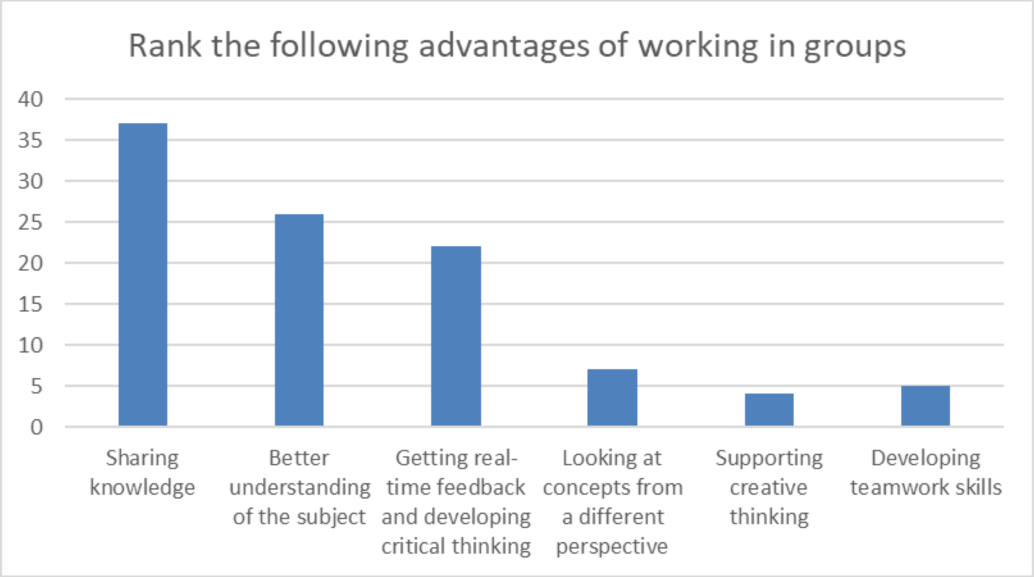


Figure 4-1 Responses to Initial Survey Question 1

Students identified that working in groups helped them to gain a better understanding of the subject by allowing them the opportunity to share knowledge and obtain real-time feedback. Most students ranked developing teamwork skills as the lowest advantage, indicating they were not using groupwork to develop their skills in teamwork, but to enhance their learning process by exchanging information and developing their critical thinking skills. The findings are consistent with the design features identified in the literature in Section 2, where social interaction and help features were important.

Students were then asked to rate their agreement with four questions regarding the objectives of working in laboratories. Their responses are shown in Table 4-2.

Table 4-2 Responses to Initial Survey Question 2

	Laboratories help me to learn how to use the equipment	**Laboratories help me to understand theoretical concepts and models**	**Laboratories help me to improve my critical thinking and analytical abilities**	**Laboratories help me to develop the ability to design experiments**
Strongly Agree (1)	69	36	25	28
Agree (2)	23	51	42	40
Neutral (3)	4	8	23	20
Disagree (4)	1	2	4	7
Strongly Disagree (5)	2	2	3	3
Mean	1.42	1.82	2.15	2.15
Standard Deviation	.80	.83	.96	1.02
Percentage Strongly Agree or Agree	93%	88%	68%	69%

For all four questions, most of the responses fell into the strongly agree and agree categories, indicating an overall positive impression about the objectives of working in laboratories. A paired t-test is used to determine if responses are significantly different than neutral, and all are statistically significant ($p < .05$). The students felt that the objective that is most satisfied by working in laboratories was learning how to use the equipment, or instrumentation. In Table 4-3, the responses to the question "*Rank the following methods for laboratory and practical work in terms of your preferred working style*" are shown along with the percentages of responses in Figure 4-2. Again, the margin of error for 90% confidence interval is 3%.

Table 4-3 Responses to Initial Survey Question 3

Option	Responses	Percentage %
On my own during scheduled classes	24	24%
In a group during scheduled classes	41	40%
On my own during my own time	13	13%
In a group during our own time	8	8%
Watching a demonstration by the lecturer	13	13%

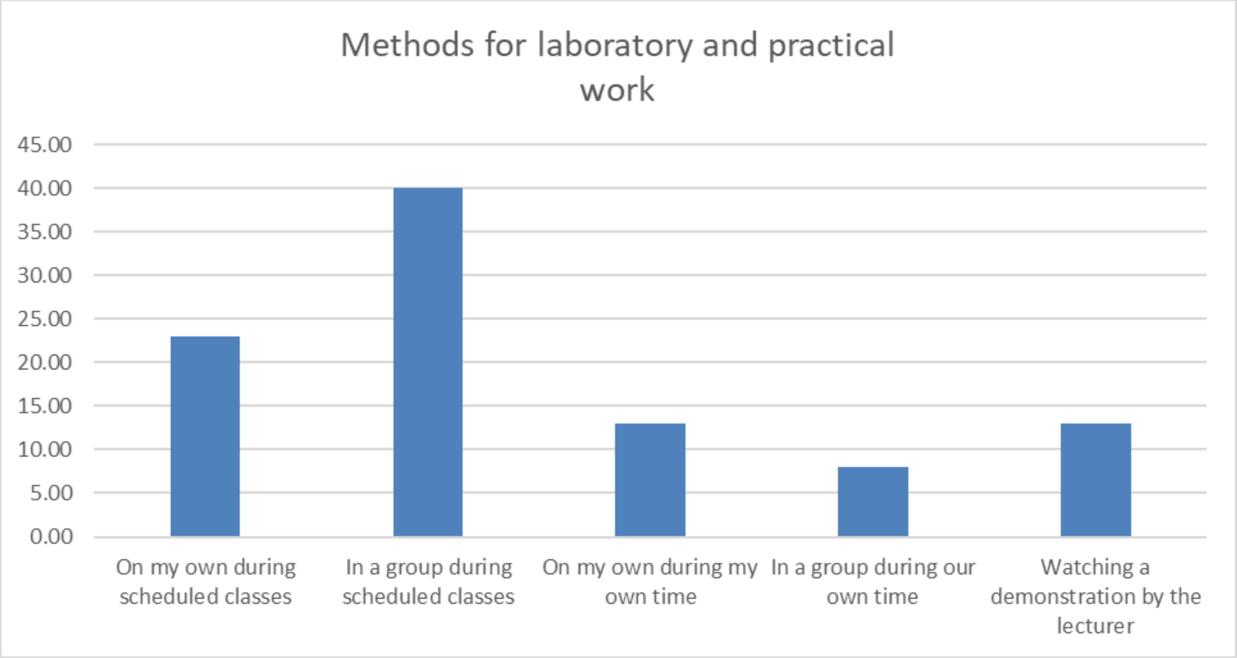


Figure 4-2 Responses to Initial Survey Question 2

Students identified that working in groups during scheduled classes was the highest-ranking preferred method, followed by working on their own during schedule classes, accounting for over 60% of the total. The margin of error of 3% indicates that the top two choices are clearly distinguished from the others, however, the bottom three choices cannot be distinguished with the margin of error. The lower rankings for "in my own time" choices may indicate that while group work is important, the scheduled time frame is more important to more students. The ability to work location-independent and in a time-independent manner did not outweigh the need for group work, and more students preferred doing laboratory work as scheduled than performing experiments in a more leisurely manner at home. However, over 20% of the students did indicate that they preferred working on their own time, perhaps indicating a need for an individualized approach to scheduling. There was no mention in the literature regarding a need for scheduled interactions for student work, however a need for individualized learning was identified.

4.1.3 Results from Open-Ended Responses

Students were asked an open-ended question in the initial survey:

> *"If you were provided with access to the laboratory equipment remotely by web interface, what would be the most important features to you in the software?"*

The open-ended responses and interviews were analysed for keywords that could categorize and summarize the responses. Students generally responded in a positive manner, identifying features they prefer as opposed to naming features they did not prefer. The findings from the open-ended question in the first survey are presented in Figure 4-3.

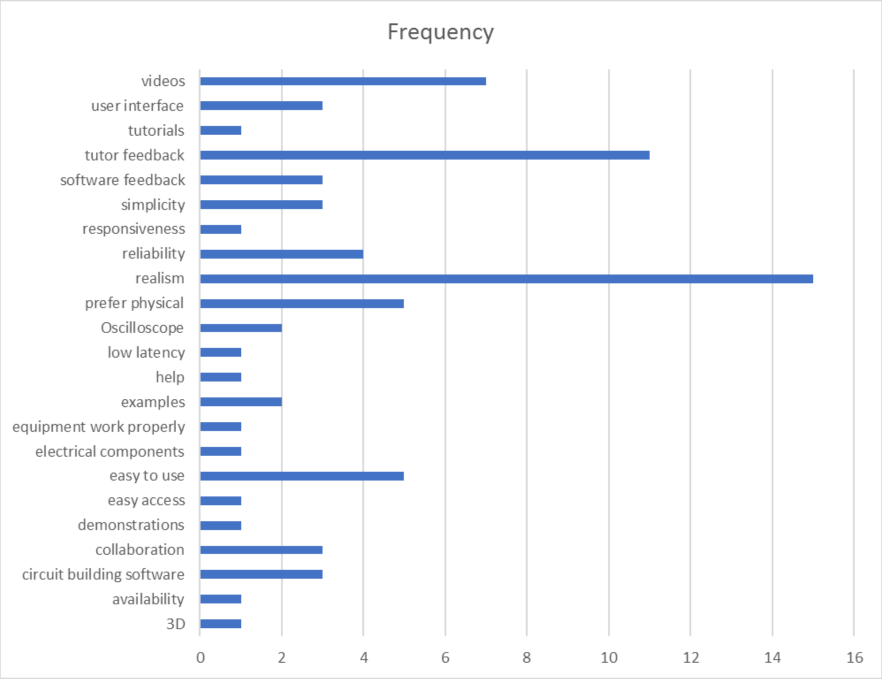


Figure 4-3 Analysis of Open-Ended Responses from the Initial Survey

The most important topic in these open-ended responses was realism. Students want the virtual laboratory to accurately simulate reality. They are also interested in feedback, particularly from their tutors and an ability to collaborate with their teammates. Many of the students mentioned chat features and real-time feedback from either the tutor or the software. Videos and online help with tutorials and/or videos were frequently mentioned. These survey responses show that students were interested in learning and skill development as well as their knowledge and desire assistance to meet their learning objectives. The students identified mechanisms that enable a better implementation of a virtual laboratory, in the sense that while they are not in the physical laboratory with live tutors, there are tools that can be provided in a virtual laboratory to compensate.

The initial survey results suggested that an important issue for virtual laboratories is the functionality and reliability of the software, and how much it resembles real equipment. Students looked for an intuitive user interface, with high speed, responsiveness, stability and accuracy. They were also looking for live support and immediate feedback from their tutors.

In general, students enjoy working in teams. They prefer doing practical work or laboratory experiments in a group during scheduled classes as they think it results in a better understanding of the subject and lets them share knowledge and discuss the subject with other people. Students also prefer teamwork because it enables them to receive instant support and real-time feedback as shown in [114]. Most students are eager to work in groups for a few reasons, but the highest ranked reasons are because they like to share knowledge and discuss the topic among them.

4.1.4 Using the Initial Survey Results in the Prototype Design

This initial survey by students was useful and it guided the design of the virtual laboratory. Their requirements about the simplicity, simulating reality, high speed and reliability of the software were considered during tool design and these requirements aligned with design features identified in the literature (Table 2-3). Students also indicated a preference for supplementary videos and an easy-to-use interface. Being able to share knowledge was important to the students, as well as working in a group during schedule classes. Yet many of the students preferred working on their own time, indicating their need for flexibility. Students also indicated that feedback was important. The feedback from the pre-design survey was used as follows.

The preferred laboratory working style was work during scheduled classes, plus one of the more higher-ranking open-ended comments was a preference for physical laboratories. This suggested that the prototype virtual tool should be an addition to the physical laboratories, and not a replacement for physical laboratories. To ensure a smooth transition between virtual and physical labs, and to address the preference for realism, it was decided to design the prototype lab to appear close in appearance to the physical lab. Rather than giving some sort of circuit schematic input, it was decided to replicate the visual experience of a circuit breadboard, with virtual wires connecting virtual components, voltages sources and multimeters.

Several students indicated that they wanted a tool to be available via their Learning management System (Blackboard) for easy access while they prepared for their class and examinations. Compatibility with the web-based Blackboard is best achieved by designing a web-based application that can be used at any time. Exploring new circuit design was also of interest, indicating that students were likely to be using the virtual laboratory to supplement their physical laboratory work. This can be achieved by allowing arbitrary circuits to be designed, not just a subset of pre-designed templates.

The students indicated that important issues were the availability of video tutorials, and that the tool should be easy to use. This fed into the tool design by ensuring that interfaces were intuitive, and that there was sufficient on-line documentation and demonstrations to allow the user interface of the tool to be quickly mastered.

The goal for the initial prototype was to provide a highly available and reliable web-based application that provided a high level of realism in the form of a breadboard simulator. While videos were desired by the students, the time and production resources required to produce high-quality videos were not available to the researcher. Instead, this comment was taken more broadly as a request for adequate tutorial information about how to use the tool, so a Quick User Guide was provided in the design. The initial prototype for the virtual laboratory was a circuit analysis laboratory used in courses covered within the first year ENGG1300 course (approximately 500 students per semester).

4.1.5 Impact of Literature Review on Design

From the literature review, there were two concepts presented that impacted the design the most: providing an easy-to-use interface and providing realism. In the literature, it was noted that a simulation tool can be just as effective as a physical laboratory in supporting the learning process of the students [39]. For prototyping circuits and learning electronics, breadboards are important tool for students to use. In addition, online teaching and online learning has continued to increase in popularity. It was a design objective to develop an online breadboard simulator that could support the learning process of the students that could be as effective as a physical laboratory.

From the literature, it was clear that an easy-to-use interface is important [46], [88], [72]. This was a key concept in the design, because there was an enthusiastic desire for the students to accept and use the tool. Realism was another important concept identified in the literature [88], [14], [79]. The goal for the design was to provide realism so that the learning laboratory closely approximated the learning laboratory that was currently used by the first-year students. It was a design objective that the laboratory would provide as much realism as possible to support students becoming familiar with how breadboards work and how currents and voltages are measured.

Other important concepts that were a high priority in the design were the ability of providing an easy to understand method for conducting experiments where students could build and simulate circuits with both resistive and non-linear loads. To support individual usage, a flexible web-based design was chosen that could be used on both mobile devices and computers.

4.2 Project Design

Based on the initial survey the virtual laboratory prototype was designed to be a breadboard simulator for electronic circuits (DC based) and allowed students to connect components like resistors, diodes, voltage sources and meters on the virtual platform in a manner similar to a real breadboard. It allows them to simulate the results in the form of current and voltages based on real mathematical data and formulas based on the circuit simulator Ngspice. The app makes heavy use of modern web browser features like JavaScript, DOM manipulation, SVG graphics and AJAX. The tool is different from a standard simulator because its user interface is designed to mimic the experience of working in a real laboratory. The same user interface could be used to interface to physical tele-operated equipment, and so is suitable for both a simulation laboratory and a remote laboratory.

The virtual electronic circuit simulation laboratory system enables users to assemble circuits on a virtual breadboard and simulate these circuits using a remote server running SPICE3f5. The tool is called UQEEVL (UQ Electrical Engineering Virtual Laboratory) and it allows students to conduct virtual versions of their classroom experiments at any time and obtain results. Electronic circuit components were designed to be dragged and dropped into place on the breadboard. Once users log in, they can then create a new project and drag components into the schematic drawing.

A trusted domain at EAIT was registered for our tool at UQ (https://virtual-laboratories.eait.uq.edu.au). Ngspice release 23 has been installed on a remote server. Ngspice is based on three open source software packages: Xspice, Cider1b1 and Spice3f5. There was a need for three separate programs and these are explained below:

1. A custom Java-based circuit editor that operates using an Internet browser, and generates circuit diagrams and netlists and is able to display simulation results
2. A web-server application that provides communications between the student user-interface client and the remote simulation server. An example of this is currently operating on the University of Queensland's webserver.
3. A simulation package that inputs circuit netlists and outputs circuit waveforms, voltages, etc. Users never access this package, only the webserver does. This could run as a separate remote simulation server receiving requests, or it could be executed as a sub-program by the web-server each time a request is received. Figure 4-4 below illustrates how the system works.

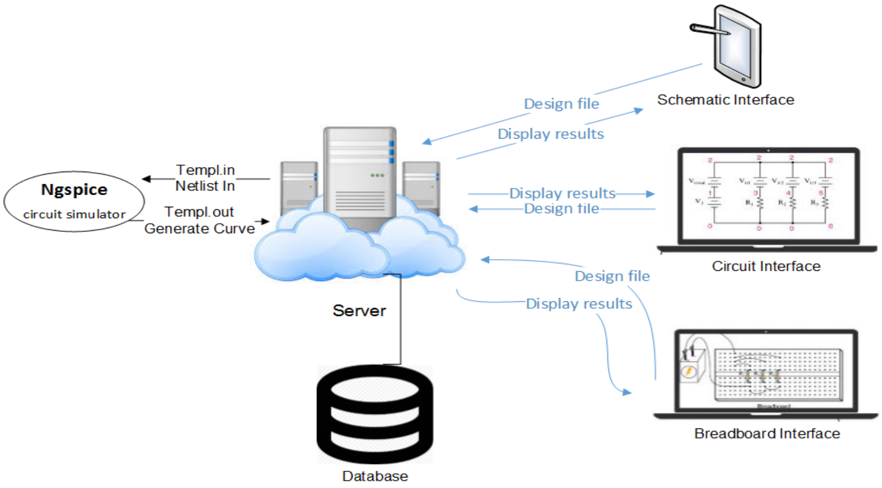


Figure 4-4 Lifecycle of the Simulation Software

When a circuit is ready to be simulated, the breadboard representation of the circuit is converted into a netlist suitable for input to SPICE. The netlist is sent by the webserver to the simulator. The circuit is solved by SPICE and the simulation result is then sent to the user's browser window. In

Figure 4-5, the overall flow chart of circuit simulator is shown. In addition to the current 'breadboard' view, it would also be possible to use the same framework to design circuits from a schematic view. User could assemble and complete the circuit with necessary components in both views and also experience the 'look and feel' of live laboratory work. The software has been tested to work on Ubuntu Linux version 14.04 LTS.

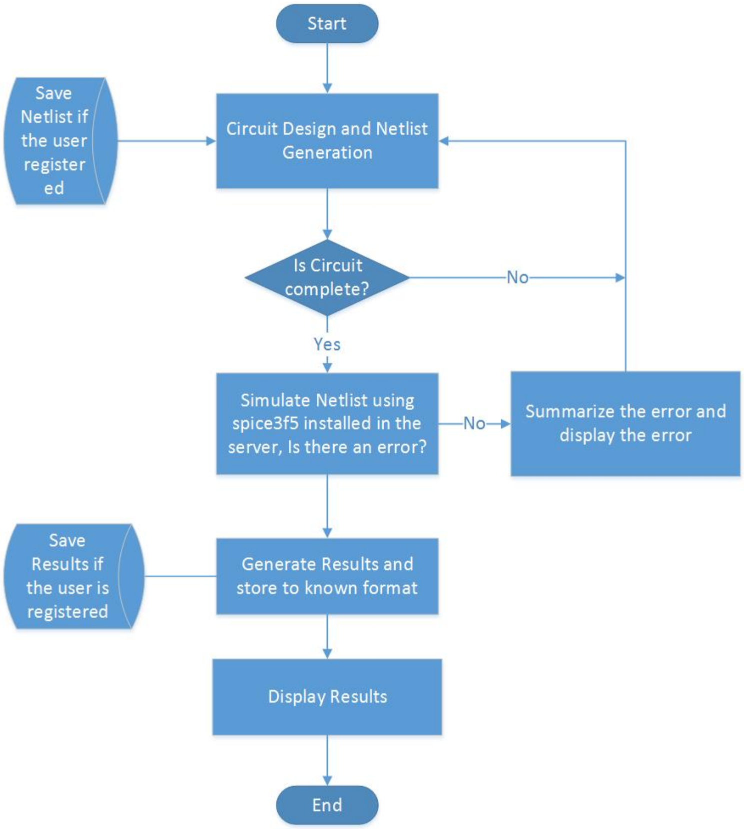


Figure 4-5 Flowchart of Circuits

4.3 Project Implementation

The following approach was taken in the implementation of the web-app simulator components. Obstacles to the implementation of the project will be discussed, along with the steps taken to resolve any issues as they arose. Figure 4-6 outlines this design procedure.

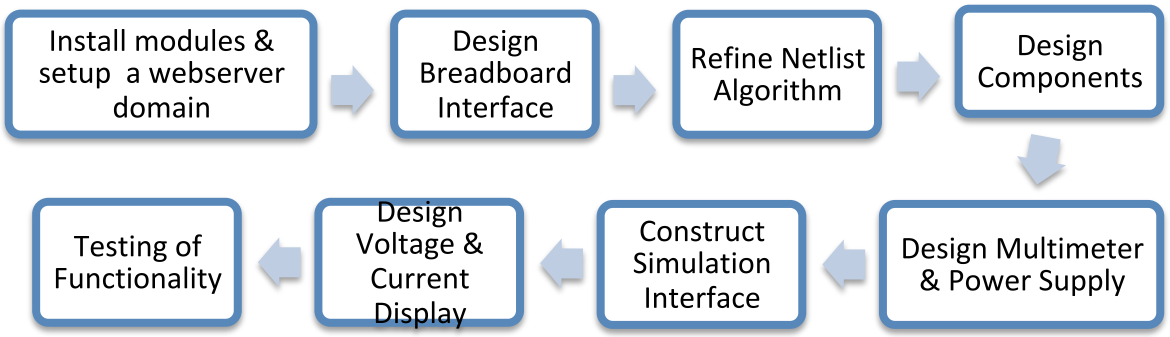


Figure 4-6 Process Design Flowchart

4.3.1 Installation of the Software and Packages

This web-app used an **Express.js web framework** and a **Node.js server**. The model used by Node.js is an asynchronous I/O model that is event-driven, which makes it well-suited to this particular study. Node.js allows for the single-page setup of the web-app, which makes it possible to perform simulations without having to reload the page. In this process, download and installation of Ngspice was undertaken, then the School's Linux server was used to host the simulation server. The process used Ngspice-26 due to its being open source and having clear and explicit instructions for usage.

4.3.2 Breadboard Design

The breadboard was comprised of three key components:

I. A grey image in the background
II. Four hidden grids for each of the breadboard's portions
III. Connectable nodes aligned with each section of gridline
IV. An algorithm based on the creation, movement or detachment of connections, that updates the net to which a node belongs.

See Appendix XII for screen shots of the Breadboard user interface.

4.3.3 Development of the Breadboard Connection Algorithm

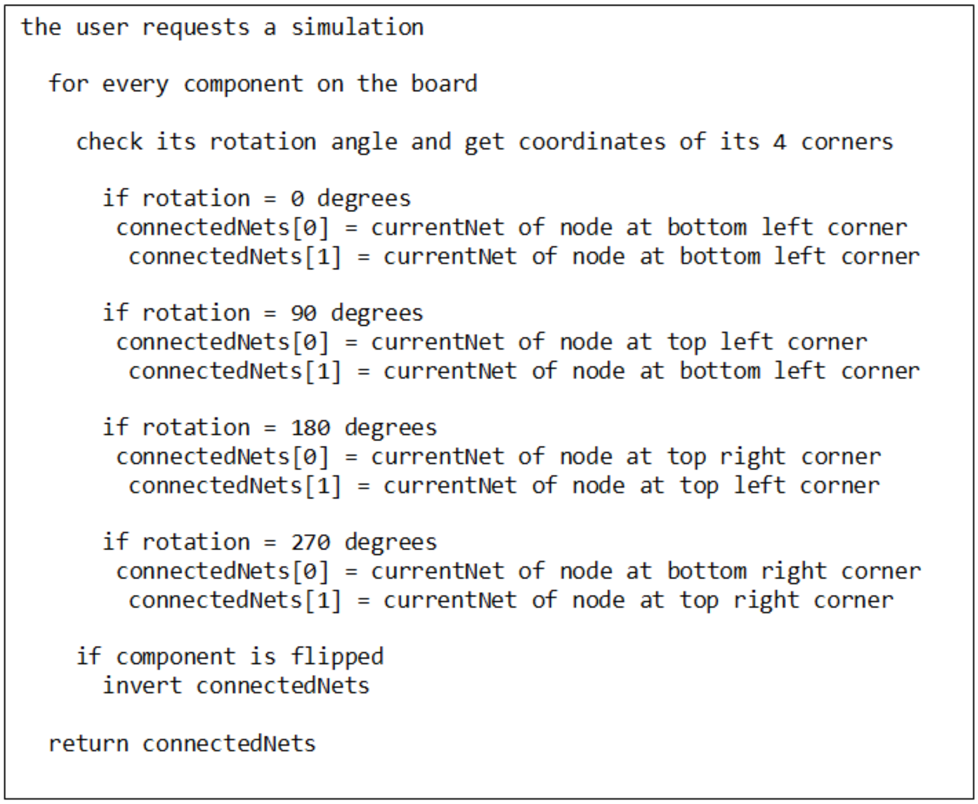
Users are able manipulate the breadboard by creating, relocating, deleting and disconnecting wires to connect nodes on the breadboard. Similar to reality, nodes that are connected in a physical manner also become electronically connected. Upon the modification of a connection, the current netlist attribute of that connection is automatically updated by the connection algorithm.

4.3.4 Designing Components

The design of the components was meant to represent real-world attributes to help students to become familiar with their real-life use. An example of this is that users will have the ability to enter into the relevant toolbar a resistance of any value between 1 and 10 MΩ, thereby prompting the simulator to automatically convert this to the closest E12 resistor value which will be visible to the user. In addition, LEDs light up to indicate that they have reached their forward voltage conditions and become burned out if the voltage exceeds these conditions. Models of components for the diodes (1N914) and LEDs are derived from the information contained on their datasheets. The following attributes are present for each component: name, value and type. A 100Ω resistor would have the following attributes:

- name = r1
- value = 100
- type = resistor

A specific name, comprising of a number and character, is given to each component. The character will be either R for resistors, D for LEDs and diodes, C for the capacitor, L for the inductor or U for an IC. The number corresponds with the number of newly added components to the breadboard, allowing for each of the board's components to be easily tracked by the simulator. Upon user request, the simulator will decide on the connections between the legs of each component and the nodes on the breadboard. This information forms the basis for the creation of the netlist as shown in Figure 4-7.



```
the user requests a simulation

  for every component on the board

    check its rotation angle and get coordinates of its 4 corners

      if rotation = 0 degrees
       connectedNets[0] = currentNet of node at bottom left corner
        connectedNets[1] = currentNet of node at bottom left corner

      if rotation = 90 degrees
       connectedNets[0] = currentNet of node at top left corner
        connectedNets[1] = currentNet of node at bottom left corner

      if rotation = 180 degrees
       connectedNets[0] = currentNet of node at top right corner
        connectedNets[1] = currentNet of node at top left corner

      if rotation = 270 degrees
       connectedNets[0] = currentNet of node at bottom right corner
        connectedNets[1] = currentNet of node at top right corner

    if component is flipped
      invert connectedNets

  return connectedNets
```

Figure 4-7 User Request Simulation

4.3.5 Design of the Power Supply and Multimeter

The DC power supply is configured for the provision of -12 volt to +12V, using a variable-slider voltage control. This provides students with the opportunity to experience the types of power supplies commonly found in physical laboratories. There are two terminals on the power supply, VCC and GND, and these are given default Net values of 1 and 0 respectively. This means that anywhere on the breadboard that is directly connected will have a current Net value of 0 and 1 (0 = connected to ground; 1 = connected to VCC).

While designing the measurement interface for current and voltage, consideration was given to several alternatives. These included a feature which can show measurements by simply moving the cursor over a connection or component. Another option involved plotting the current and voltage in a window, in a similar way to that found in LTspice. However, it was deduced that these options had little use in terms of teaching students how to correctly measure current and voltage in a real-life setting. Instead, it was decided that a multimeter tool that measured current in series and voltage in parallel would be the best option as shown in Figure 4-8. This tool was also modelled against real-life limitations of actual multimeters to create a more true-to-life experience.

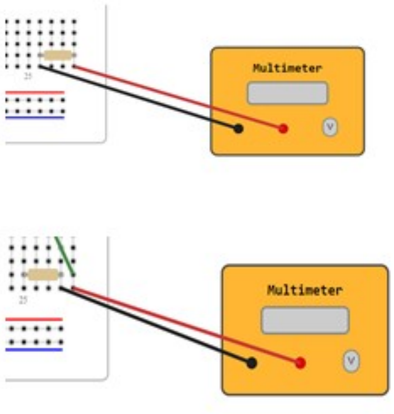


Figure 4-8 Voltage Measurement across a Resistor, Current Measurement through a Resistor

In voltage mode, the multimeter is simulated with a 10 MΩ resistor. In operations involving resistances below 1 MΩ, it will be displayed as an open-circuit with minimal flow of current, allowing for accurate measurement of voltage between two points. However, just as in reality, this measurement loses accuracy when measurements are being taken within the mega-ohm range. This is due to the voltmeter having resistance that is comparable to that of the circuit, causing a relatively significant amount of current to flow through the multimeter.

In the current mode, the multimeter is simulated as a 0.01 ohm resistor. It is imperative that the placement of the multimeter is in series with the relevant branch. If the multimeter is placed parallel to the branch, a significant current will flow via the multimeter, and the desired reading will not be produced, just as in the physical lab.

4.3.6 Building the Simulation Interface

The simulation interface is the key element of the tool and takes on the role of allowing users to undertake circuit simulation on a circuit simulator based on SPICE. An Ajax model is used by the client-server communication. Ajax allows simulations to operate in background without causing any interruptions to the appearance and function of the internet page. This feature allows single-page operation of the web-app. Also, it is unnecessary for the page to be reloaded once opened. The simulation process is shown in Figure 4-9.

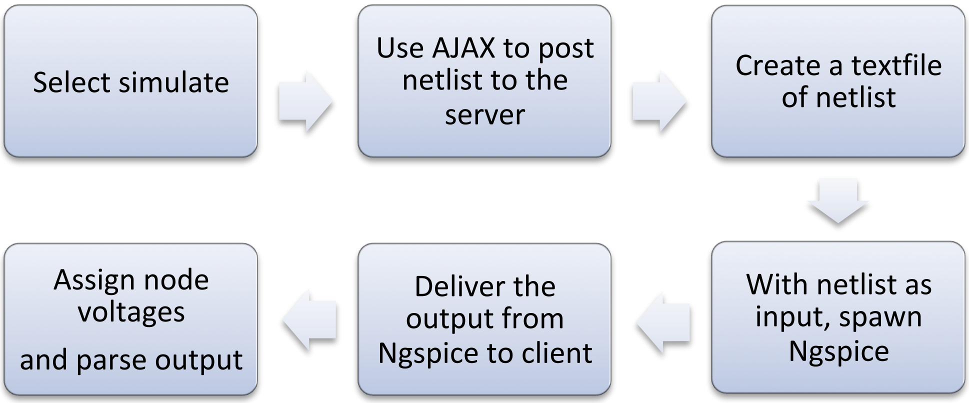


Figure 4-9 Simulation Running Process

Upon clicking the Simulate button, the simulator creates a netlist that contains the following:

- The circuit name,
- print command,
- sources of voltage,
- component models,
- command for DC analysis,
- and components.

4.4 Software Functional Testing

This section will provide a description and analysis of the results achieved from the circuit simulator's functional testing.

4.4.1 DC Resistors Networks

As seen in Figure 4-10 and Figure 4-11, the branch currents and node voltages of the circuit were measured using LTspice and the Breadboard-simulator.

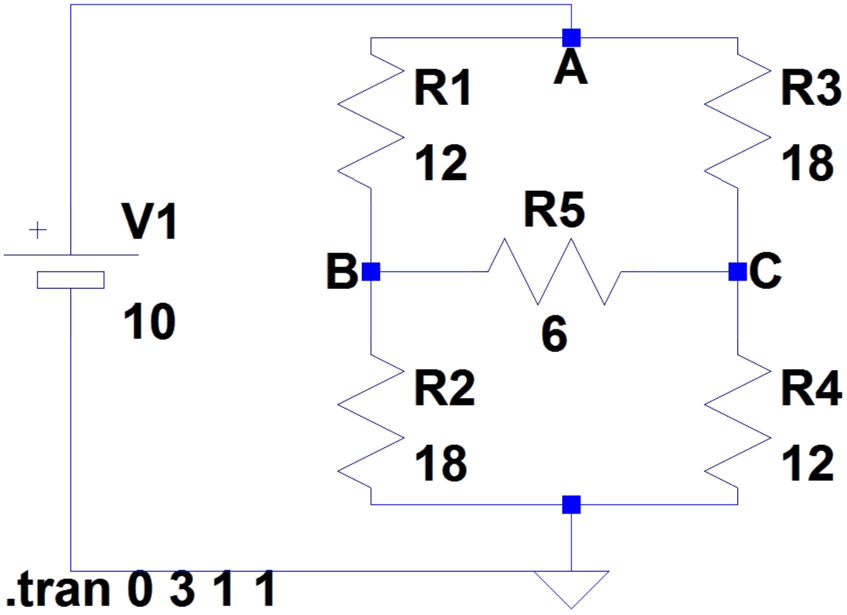


Figure 4-10 A DC Resistor Network

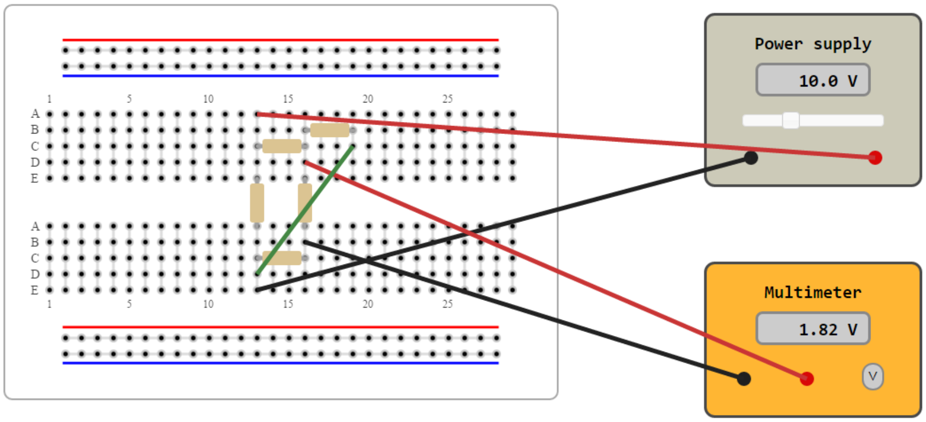


Figure 4-11 Circuit Built in the Breadboard Simulator

Table 4-4 shows the node voltages and branch currents used in the circuit. Both gave identical results once customized to simulate the circuit.

Table 4-4 Branch Currents and Node Voltages of the Circuit

	Developed Breadboard Simulator	**LTSpice**
VDA	2.72 V	2.72 V
VAB	1.82 V	1.82 V
VAE	1.82 V	1.82 V
VCD	10 V	10 V
ICD	100 mA	100 mA
IAB	36.35 mA	36.36 mA

4.4.2 LED Circuit

A simulation of the circuit in Figures 4-12 and 4-13 was conducted both in LTspice and the breadboard simulator. In it, variation for the voltage *V1* was achieved for values between 0 – 10 V at variable intervals, and measurements were taken of the voltage across and current through the LED.

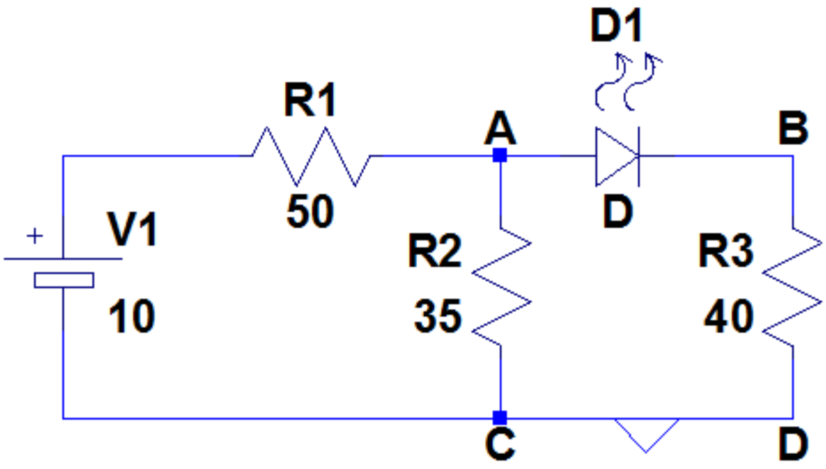


Figure 4-12 A Circuit Contains Resistors and One LED

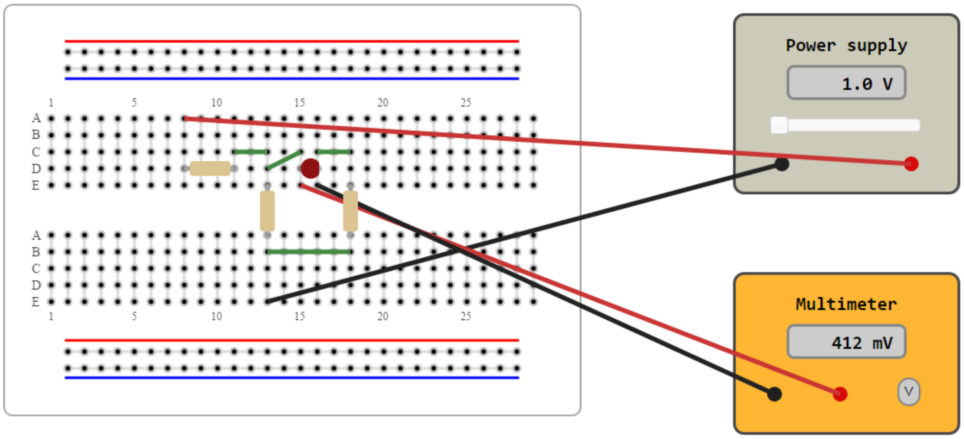


Figure 4-13 Next Circuit Built in the Breadboard Simulator

Identical results were obtained from both LTspice and the breadboard simulator. In each case, the LED indisputably showed a non-linear I-V relationship as seen in Table 4-5. The design of the LED caused it to light up to show a forward voltage between 1.8 – 2.4 V, which was visible in the breadboard simulator.

Table 4-5 Current Through and Voltage Across the LED with Various Supply Voltage

	Developed Breadboard Simulator		**LTSpice**	
V_S (V)	V_D (V)	I_D (mA)	V_D (V)	I_D (mA)
0	0	0	0	0
1	0.412	6.79	0.411	6.72
2	0.824	13.6	0.822	13.5
3	1.24	20.4	1.24	20.3
4	1.61	27.2	1.62	27.2
5	1.78	34	1.78	34
8	1.95	54.4	1.96	54.4
10	2.04	67.9	2.04	67.8

4.4.3 Complex Circuit with Non-Linear and Resistive Components

A complex circuit containing LEDs, diodes and resistors was formed in both the breadboard simulator and LTspice as shown in Figure 4-14 and 4-15. Then, measurements and recordings were taken of the voltage at each node.

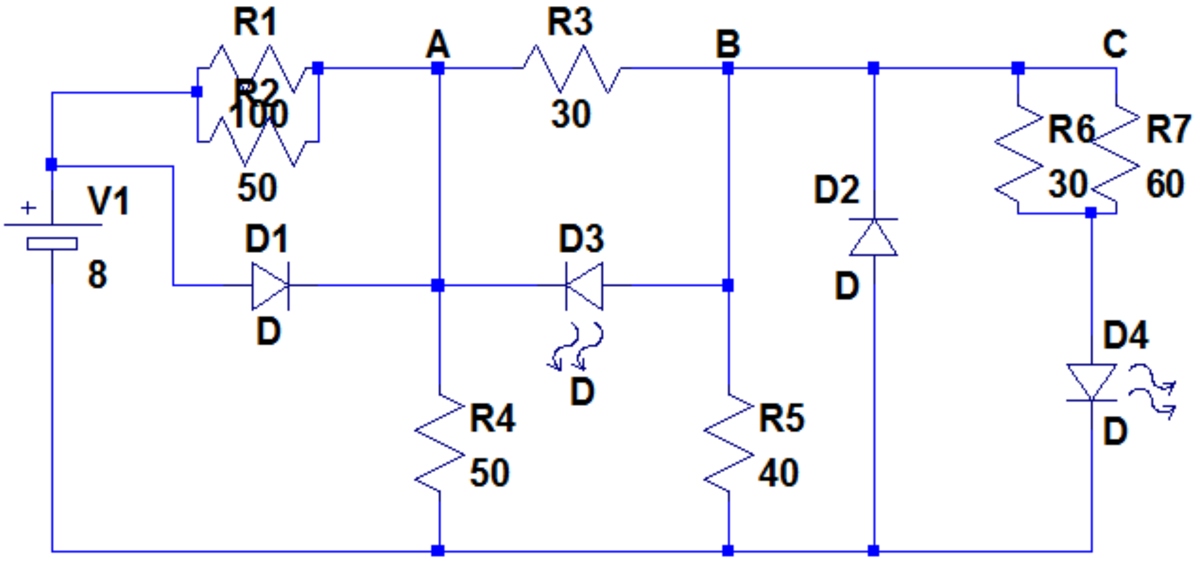


Figure 4-14 Circuit Built in LT-Spice with Diodes, LEDs and Resistors Built in LT-Spice

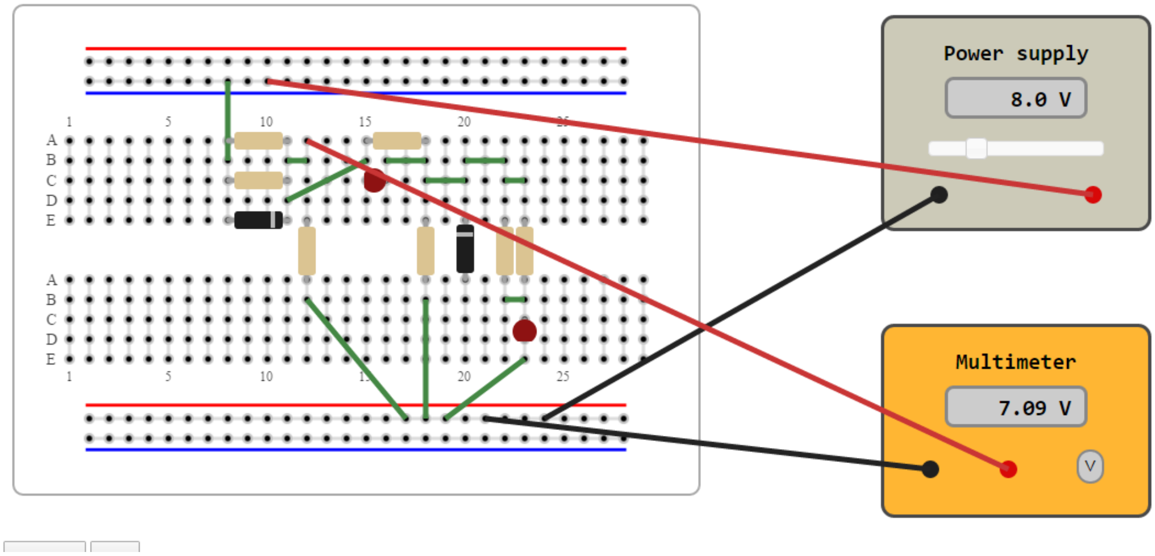


Figure 4-15 The Circuit Designed on the Breadboard

Table 4-6 shows the circuit's node voltages, measured in the bread-board simulator and LT-spice.

Table 4-6 Branch Currents and Node Voltages of the Circuit Shown in Figure 9 and 10

	Developed Breadboard Simulator	**LTspice**
$V_A\ (V)$	7.09	7.19
$V_B\ (V)$	3.38	3.32
$V_C\ (V)$	3.38	3.32

Again, simulations undertaken both in LTspice and the breadboard simulator exhibited similar voltages at each node in the circuit.

4.4.4 Circuits with Resistors and Capacitors

At this stage, the simulator only simulates DC circuits, however students can add capacitors and inductors (which operate like open circuits and short circuits at DC).

A circuit was designed in LTSpice as well as on the breadboard simulator that consisted of resistors and a capacitor, as shown in Figure 4-16 and Figure 4-17. Measurements were taken of this circuit's node voltages.

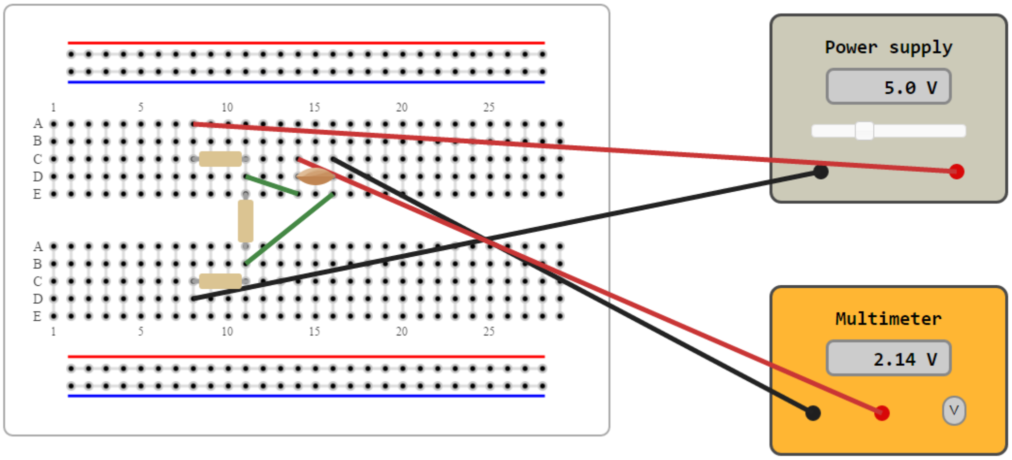


Figure 4-16 The Circuit Contains a Resistor with One Leg Not Connected to the Breadboard.

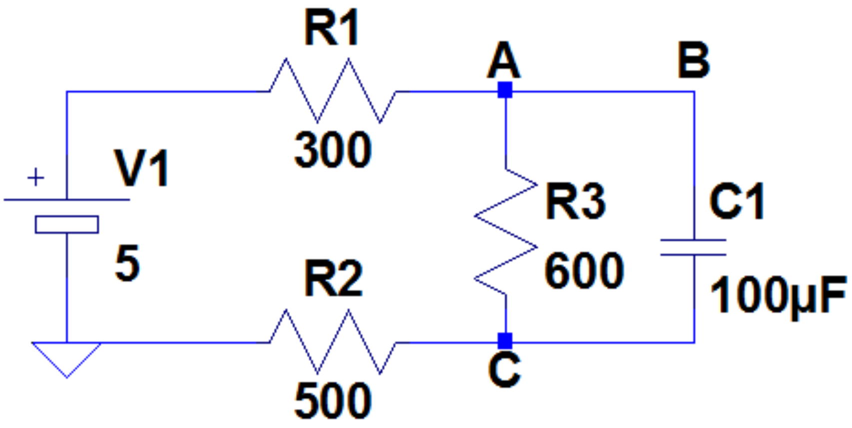


Figure 4-17 The Circuit Built in LTSpice

Table 4-7 shows the circuit's node voltages measured in the bread-board simulator and LT-spice.

Table 4-7 Node Voltages of the Circuit

	Developed Breadboard Simulator	**LTspice**
V_A (V)	2.14 V	2.15 V
V_B (V)	2.14 V	2.15 V
V_C (V)	1.78 V	1.78

Results showed that simulations done on the bread-board and LT-spice yet again displayed the same voltages for all nodes in the circuit.

4.4.5 Circuit Designed with an Intentional Short-Circuit

One branch in the DC--network shorted out, as shown in Figure 4-18 and Figure 4-19. Measurements of the circuit's node voltages were taken.

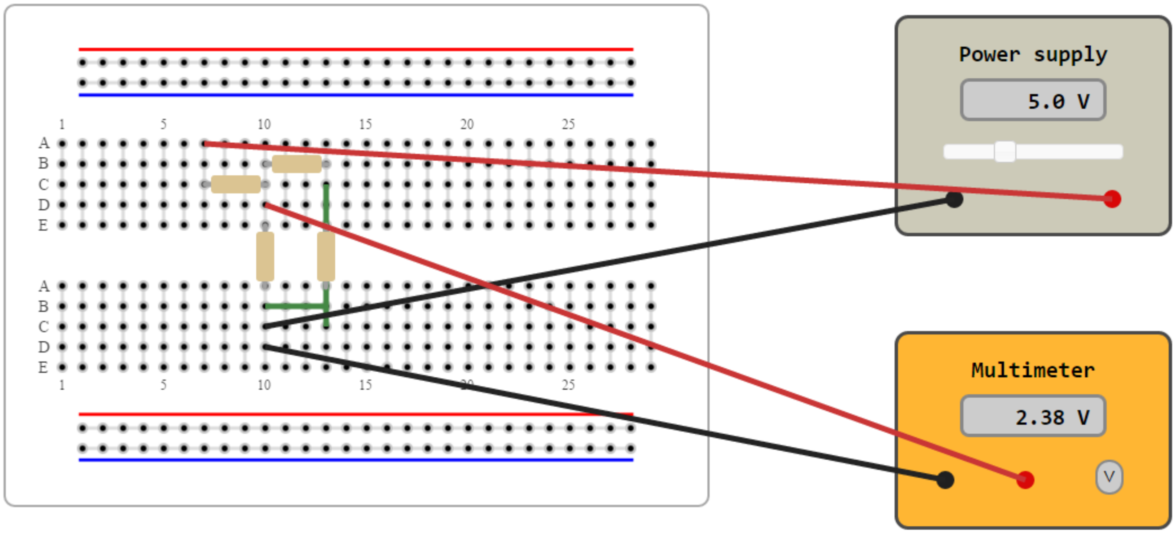


Figure 4-18 The Highlighted Resistor is Shorted Out

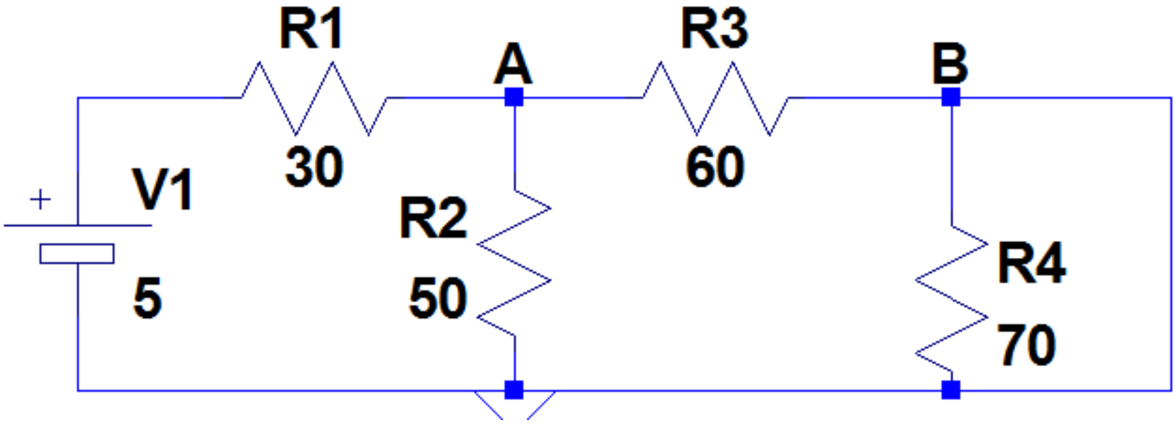


Figure 4-19 The Previous Circuit Built in LT-Spice

Table 4-8 shows the circuit's node voltages, measured in both LT-spice and the breadboard simulator.

Table 4-8 Circuit's Node Voltages on Previous Circuit

	Developed Breadboard Simulator	**LTspice**
$V_A\ (V)$	2.38 V	2.38 V
$V_B\ (V)$	2.38 V	2.38 V
$IR_2\ (V)$	47.61 mA	47.61 mA
$IR_3\ (V)$	39.70 mA	39.68 mA
$I_C\ (V)$	39.70 mA	39.68 mA

Simulations were completed in both LT-spice and the breadboard simulator; the result showed the same voltages at all nodes in the circuit.

4.5 Summary

This chapter has described a virtual laboratory prototype environment for DC circuits. The tool itself does not represent a significant research contribution, but rather demonstrates some of the principles of modern virtual laboratory software. This tool will be used as a typical environment, so that the views of students and faculty can be evaluated against a concrete example, rather than just an abstract notion of a virtual laboratory. Additionally, experience with the specification, design, implementation and evaluation of this sample tool will provide input to the later development of design guidelines.

5 Post Deployment Survey Designs and Results

Additional surveys were performed during and after the development process. These surveys are as follows.

A **Post Development Survey** was conducted after the Semester 1, 2016 deployment of the prototype simulator. To encourage maximum participation the survey was divided into two parts, so that after students had completed the first 5-10 minutes survey, students could optionally continue on to complete a second 5-10 minute on-line survey. The first part of the survey asked questions about user experience of using virtual labs, and the detailed survey questions are listed in Appendix II. The second part asked more specific questions about the virtual laboratory tool itself, and those questions are listed in Appendix III.

Following the above post-development survey, some minor changes were made to the tool (such as improved error reporting), and the tool was again made optionally available for student use in ENGG1300 in Semester 1, 2017. After this deployment, an online **Post Production Implementation Survey** was conducted to see how students used the tool during semester. These survey questions are listed in Appendix IV. Additionally, after the tool deployments, semi-structured **Faculty Interviews** were conducted with, with the interview structure listed in Appendix V.

5.1 Post Development Survey

This section describes the survey design of the post development survey, as well as the results of the survey. This includes the results from the user experience survey and the user evaluation survey.

5.1.1 Survey Design

After first deployment of the virtual laboratory prototype in Semester 1, 2016, students were surveyed to provide feedback regarding the prototype's speed, complexity, handling, reliability and control. The participants of the survey were asked to rate the virtual laboratory under different merit criteria as well as providing their perception of online laboratories after using the tool.

In Part 1 of the survey, students were firstly queried about their level of expertise with using laboratories and what versions of web browsers they used in case there was a pattern of poor performance with certain browsers or experience levels, but there were no such difficulties identified, so these results are not analysed further.

Next students were queried about their perceptions of the tool - how user-friendly they found it (5- point scale), if it freezes or crashes (it didn't), if additional documentation is needed (yes/no). Then students were asked to rank perceived advantages of virtual laboratories, as identified from the literature (better understanding, different perspectives, experimental design, understanding theoretical models). Then, students were asked about their agreement (using a 5-point Likert scale) with statements asking if virtual laboratories helped them to achieve the same four learning objectives for ENGG1300 - use of equipment, reinforcing theoretical concepts, critical thinking, and experimental design. Then they were asked about whether the simulation laboratory helped with other learning objectives in the ABET list. The complete questions are in Appendix II. This assisted in understanding student perspectives on virtual laboratories in terms of learning objectives.

Part 2 of the survey asks more specific questions about the tool itself, in terms of its usability and effectiveness. In each case, a 5-point scale (worst to best) was used. Based on the types of questions asked in similar usability surveys reported in the literature, students were asked to rate the following aspects.

- overall impression
- easy-of-use
- frustration
- power to perform experiments
- stimulating to use
- flexible
- suitable of screen items (components, wires, etc)
- meaningful terminology
- meaningful screen messages
- speed
- reliability
- ability to correct mistakes
- match to user experience
- easy of learning the tool

- suitability for new experiments
- user interface (colours, response to errors, etc)

The complete set of questions in in Appendix III.

The virtual laboratory platform was used by a total of 140 users for understanding the fundamentals of circuit implementation, based on the web-use log. Students using the platform were invited to participate in the post development survey, resulting in 116 responses out of a class of 500. For a 90% confidence level, the margin of error for this survey is 3-7%.

5.1.2 User Experience Results

The survey questions related to the user experience about the online simulator included demographic responses (see Appendix III), as well as questions related to advantages of online experimentation, using virtual laboratories and questions related to the ABET learning objectives. Statistical analyses using t-tests were performed to determine if responses significantly differed from a neutral response and for most categories the results were significantly positive ($p < .05$). The only exception was “Looking at concepts from a different perspective” that did not significantly differ from neutral.

The responses to the following question are shown in Figure 5-1: “Based on your experiences while using the software, rank the following advantages of doing experiments online (either at university or at home): (1=least advantage, 5=greatest advantage)”. The figures show the count of responses in each response category.

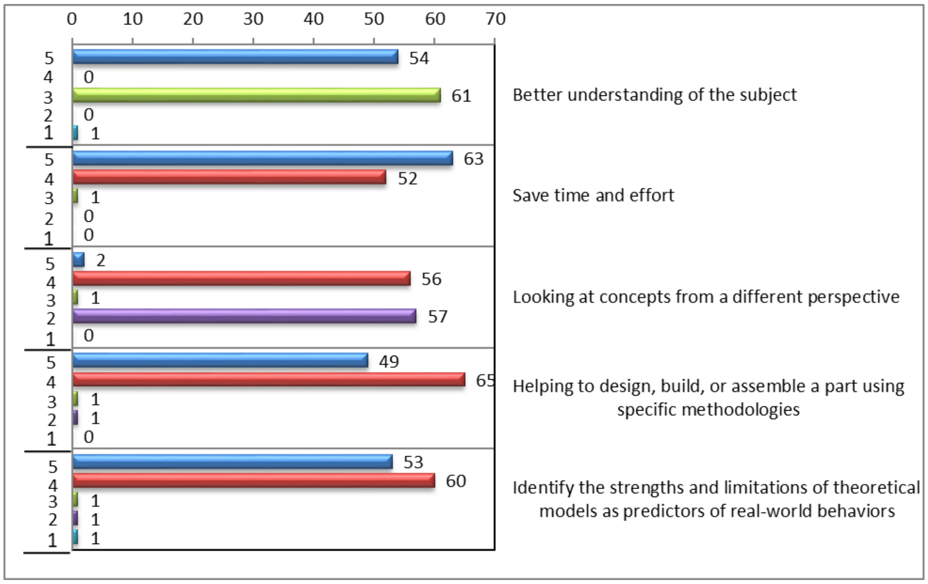


Figure 5-1 User Experience – Advantages of Online Experiments

The response "Save time and effort" had the most responses (63) in the "greatest advantage" category (54%) followed by "Better understanding of the subject" at 47%. "Looking at concepts from a different perspective" had the most negative responses at 49% of the total responses. Overall, students felt significantly positive about saving time and effort, designing, building or assembling parts and identifying the strengths and limitations of theoretical models as predictors of real-world behaviours when performing experiments online.

The next question asked respondents to "Select the level to which you agree with the following statements:" and the response counts are shown in Figure 5-2. Most responses fell into the "Strongly Agree" and "Agree" categories, however responses were more neutral regarding the use of virtual laboratories to improve critical thinking and analytical capabilities. These questions specifically refer to learning objectives and the students clearly perceive after using the Breadboard Simulator that virtual laboratories are helpful in achieving the learning objectives of instrumentation, understanding theoretical concepts, critical thinking and analytical abilities, and designing experiments.

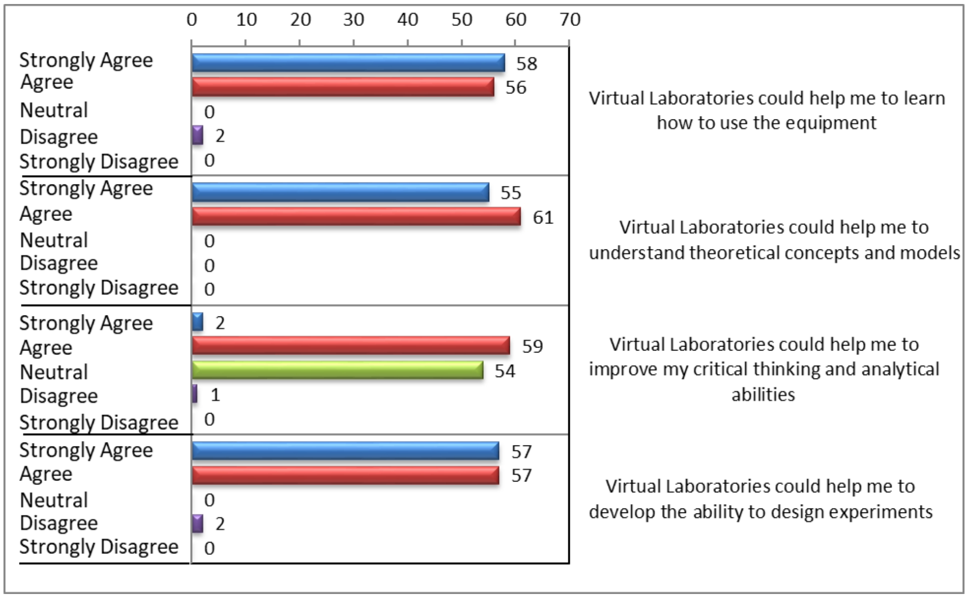


Figure 5-2 User Experience – Perception of Virtual Laboratories

Students were also asked about the use of simulation related to instrumentation or the application of appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities. The responses, shown in Figure 5-3 indicate that students felt strongly that simulation helps use components effectively and accurately. Most responses fell into the “Strongly Agree” or “Agree” category, indicating overall that students felt positively about using simulation for learning instrumentation.

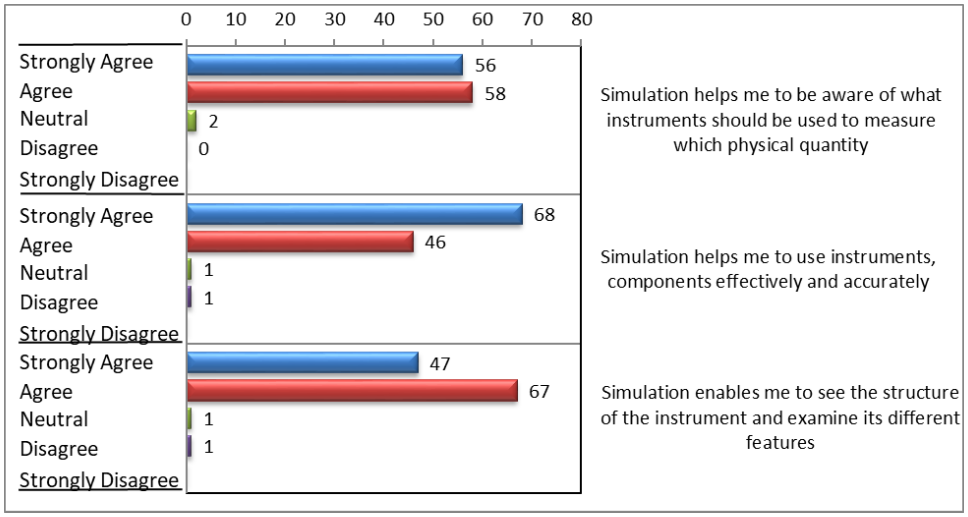


Figure 5-3 User Experience – Use of Simulation and Instrumentation

Students were asked about the use of simulation to improve their creativity as an engineer and asked if they agreed with the statements shown in Figure 5-4. Again, overall students felt positively about using simulation with almost 70% agreeing strongly that “Simulation allows more time for creativity.”

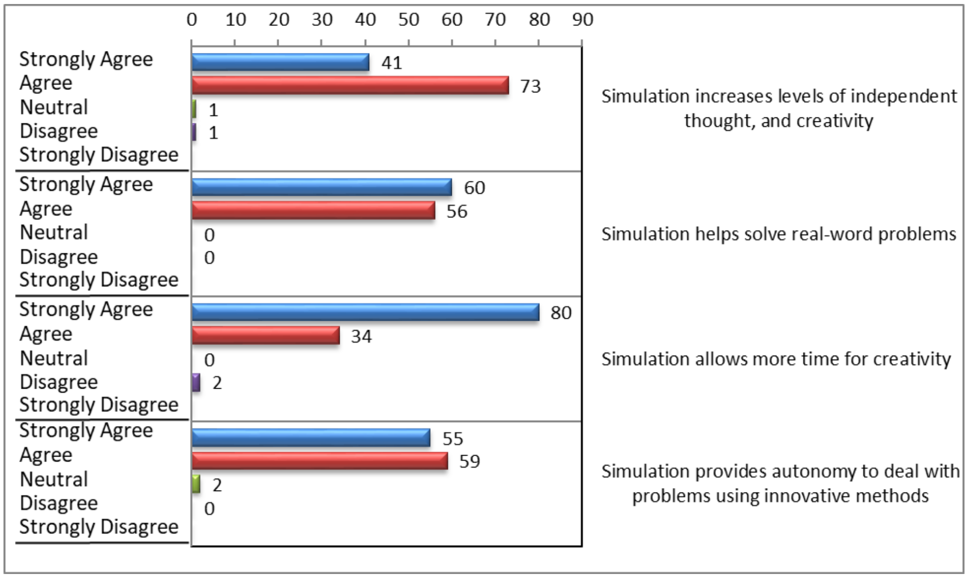


Figure 5-4 User Experience – Use of Simulation and Creativity

Overall, students felt positive about online experiments and the use of simulation. They tended to feel most strongly about the ability of virtual laboratories and simulation to allow them more time for creativity and the ability of online laboratories to save them time and effort.

5.1.3 User Evaluation of an Interactive Breadboard Simulator

The data collected in the second part of the post development survey is shown graphically below. Response values ranged from 1, indicating a strong negative response to the relevant question, to 5, indicating a strong positive response to a question. Responses with values of 1 and 2 were grouped into the “Poor” category, responses with a value of 3 were classified as “Average” and responses of 4 and 5 were classified as “Good”. The graphical results display the percentage of responses that fell into “Poor”, “Average” and “Good”, totaling 100%.

The responses are shown in Figure 5-5 and were overwhelmingly favourable. Statistical analyses using t-tests were performed to determine if responses significantly differed from a neutral response and for most categories the results were significantly positive ($p < .05$) with the following exceptions:

- Consistency of message on input prompts was significantly negative
- Response to errors was not significantly different than neutral

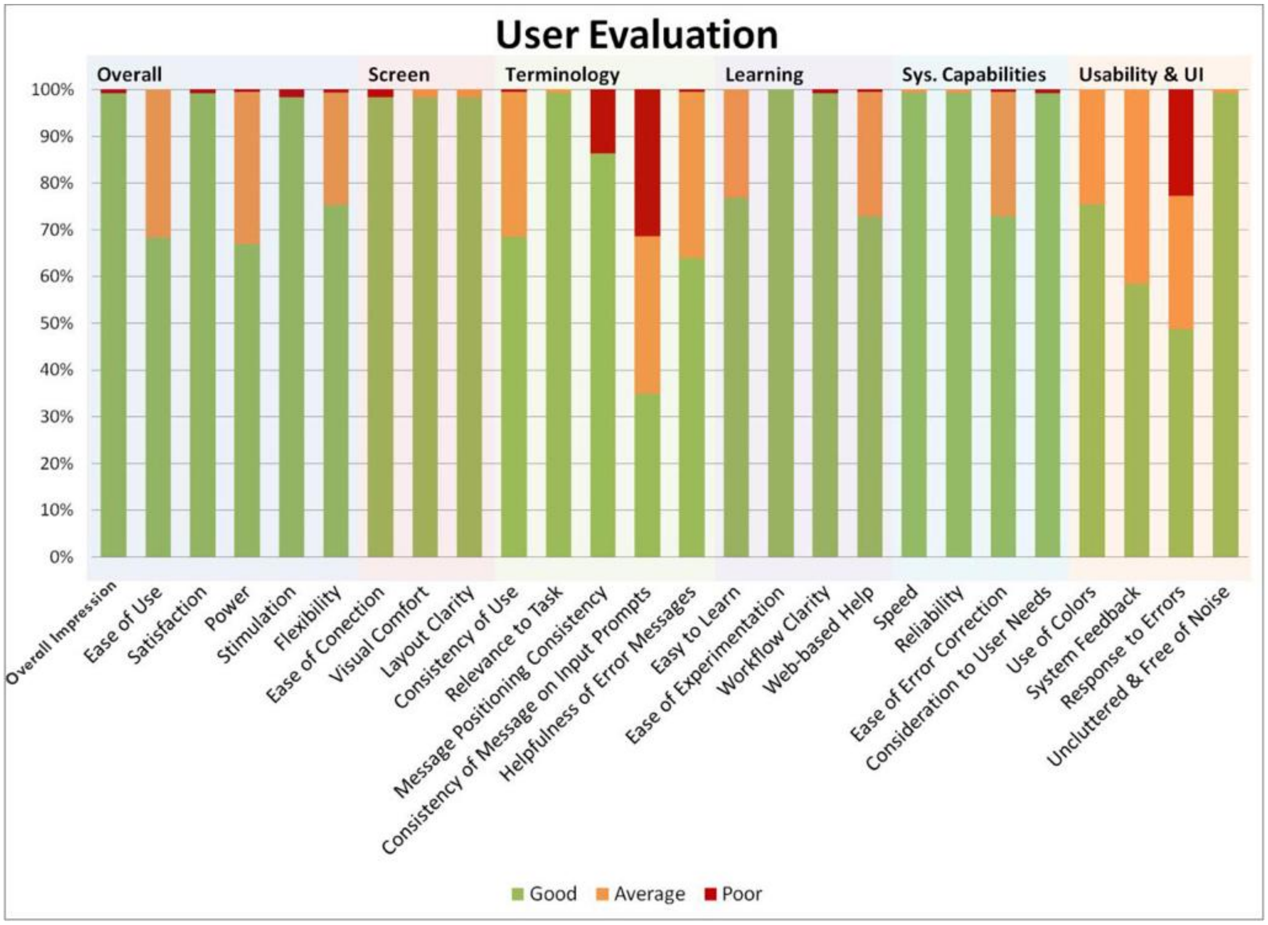


Figure 5-5 User Evaluation of the Simulator

A high-level summary of the results and the evaluation of the screen components is shown in Figure 5-6. Overall, the software was favoured by the survey respondents, though they would have been happier with more ease of use, and greater power and flexibility. The students felt positively about the screen components, only demonstrating a few issues with the ease of connection.

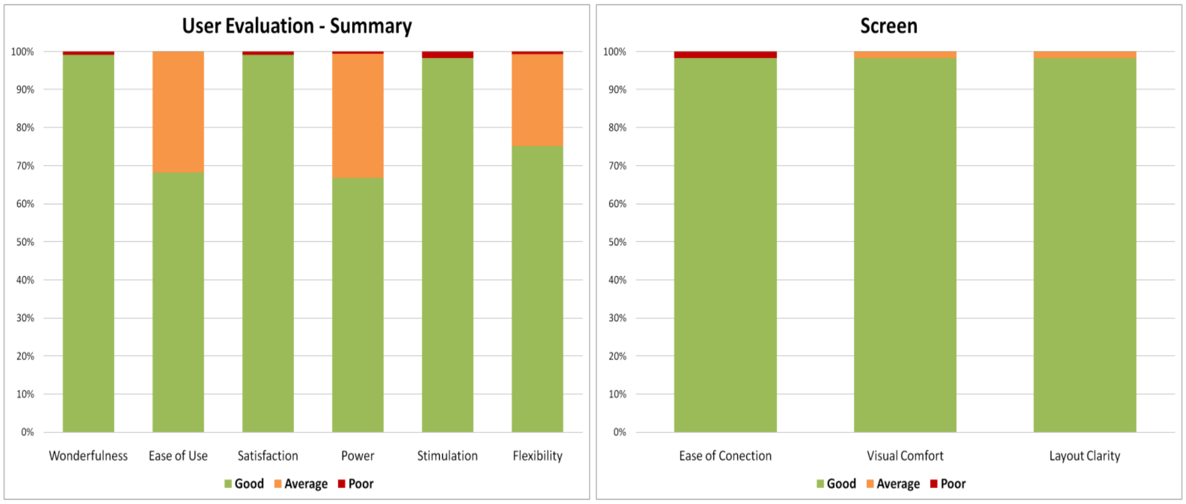


Figure 5-6 Summary and Screen Evaluation

As shown in Figure 5-7, it is apparent that Terminology Usage was an area where the software needed improvement. More specifically, messages needed to be consistent on prompts seeking user inputs, and the system needed to be better at responding to errors during experiments. A system may also gain greater acceptance by applying consistency in its usage and message positioning, increasing helpfulness of error messages, improving help content on its website, supplying a provision for better response to errors, improved feedback, and slightly better use of colours as shown in Figure 5-8.

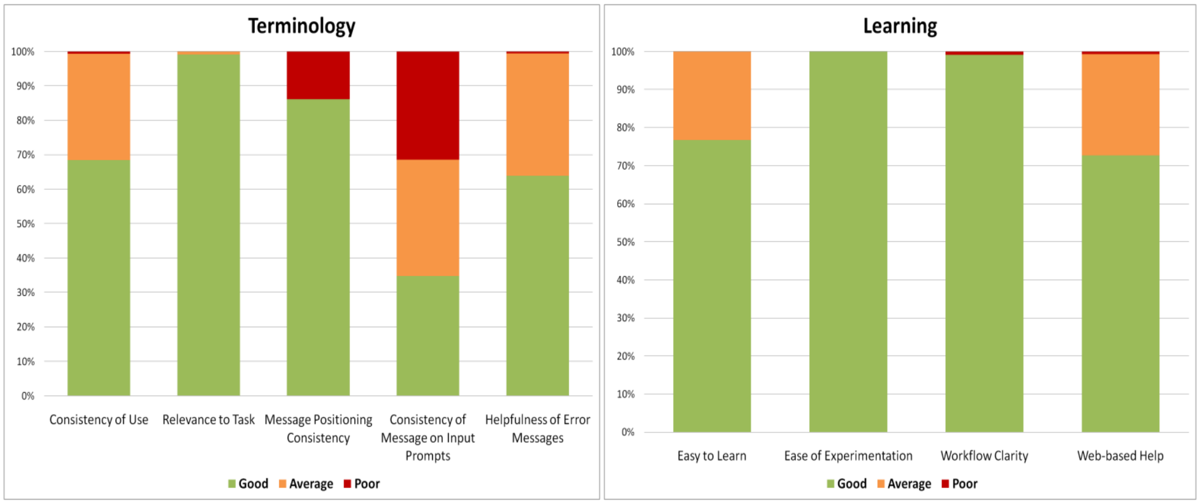


Figure 5-7 Terminology and Learning Evaluation

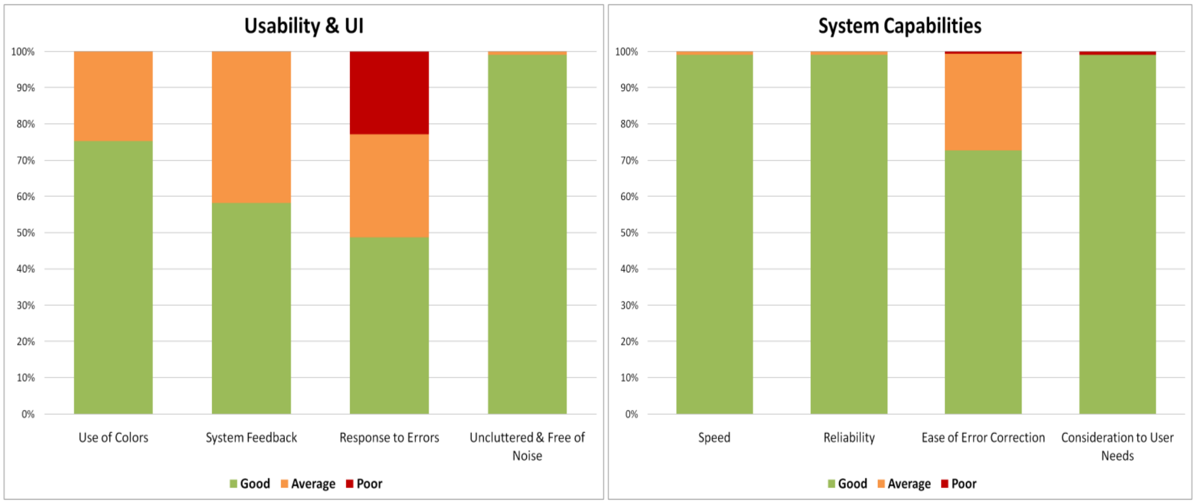


Figure 5-8 Usability and System Capabilities Evaluation

5.1.4 Summary of Student Feedback from the Post-Development Survey

After the feedback was obtained from students regarding technical features expected from the virtual lab, the designers made every effort to ensure that each of these aspects were addressed in the prototype. Specifically:

1) ***Simplicity and Usability***: The prototype was designed to be minimalistic without an excess of options and unnecessary functionality. It was designed specifically to be tailored towards the circuit design laboratory and usability was given special attention. A drag and drop functionality was implemented to minimise any confusion and to ensure that the virtual laboratory resembled the physical laboratory, thus eliminating any need for technical knowledge in using the virtual lab.

2) ***Speed and reliability***: Given that this was high on the list of students' technical requirements, the prototype was ensured to be fast in loading and simulation.

3) ***Visual clarity***: The screen related aspects, visual ease, readability etc. were given particular consideration as the designers realised this is one of the most crucial aspects of a virtual laboratory to avoid students being repelled by the discomfort in staring at the screen which would not be the case in a physical lab.

4) ***Learning and Experimentation***: The designers ensured that although the prototype was designed to be minimalistic, it still had sufficient functionality to allow students to perform various experiments within the bounds of this laboratory i.e. circuit design.

As discussed in the previous section, each of the above considerations was seen to be addressed either favourably or satisfactorily by students indicating that the pre-survey concerns were addressed. However, in surveying the students in a detailed manner on various sub-factors, a new factor to be addressed was discovered: clear response to errors. This was not highlighted in the initial survey and wasn't directly addressed during the design and was considered to be poorly addressed according to 10-30% of students. This can be seen in their feedback on three factors:

- Message positioning consistency
- Consistency of message on input prompts
- Response to errors

These were the only responses with a high number of students responding with "poor" and they were all related to the way in which messages were displayed or errors were dealt with. It shows that not only do designers overlook certain aspects of virtual laboratories as they do not share the same perspective, but that this may occur despite an initial survey with students where such details may still be missed. Thus, a second survey is necessary after students have had an opportunity to use a first version of the virtual laboratory prototype so that a second version may successfully address all aspects of the student perspective.

In the literature user interface, realism, individualization, storage capacity, social interaction, simplicity, multimedia features, help features, and qualified technical staff were identified as important design considerations in virtual laboratories. The survey responses support findings in the literature, such as a quality user interface and simplicity for designing experiments. This is consistent with the findings in [89], where students rated reliability to have the third highest rating on importance and in [88] where "easy understanding and usage" was one of the top requests in a virtual laboratory.

5.2 Post-Production Implementation Survey

This section describes the survey design for the post-production implementation survey. The results follow the discussion of the design.

5.2.1 Post-Production Implementation Survey Design

The post-production implementation surveys were presented to provide information that could help determine how virtual laboratories can best be used in conjunction with physical laboratories. The revised tool was made available to ENGG1300 students throughout semester 1, 2017. At the end of the semester, students who used the tool were asked to evaluate how well they agreed with statements that physical labs helped them achieve laboratory learning objectives, and also how well they agreed with statements that virtual labs helped them achieve laboratory learning objectives. Then they were also asked about how well they agreed with statements regarding some of the previously claimed advantages and disadvantages of virtual labs, such as more time to complete experiments, unavailability of tutors with virtual labs, etc. The complete list of questions is in appendix IV. The survey responses used a 5-point Likert scale where 1=Strongly Disagree and 5=Strongly Agree.

5.2.2 Post-Production Implementation Survey Results

The averages for responses to the 13 ABET derived questions for physical laboratories and the Breadboard Simulator are shown in the Figure 5-9 below. The survey responses used a 5-point Likert scale where 1=Strongly Disagree and 5=Strongly Agree.

The number of responses varied from 10-15, so the sample size was small reflected by a margin of error of 25%. The analysis of this data will look only at broad trends in this data.

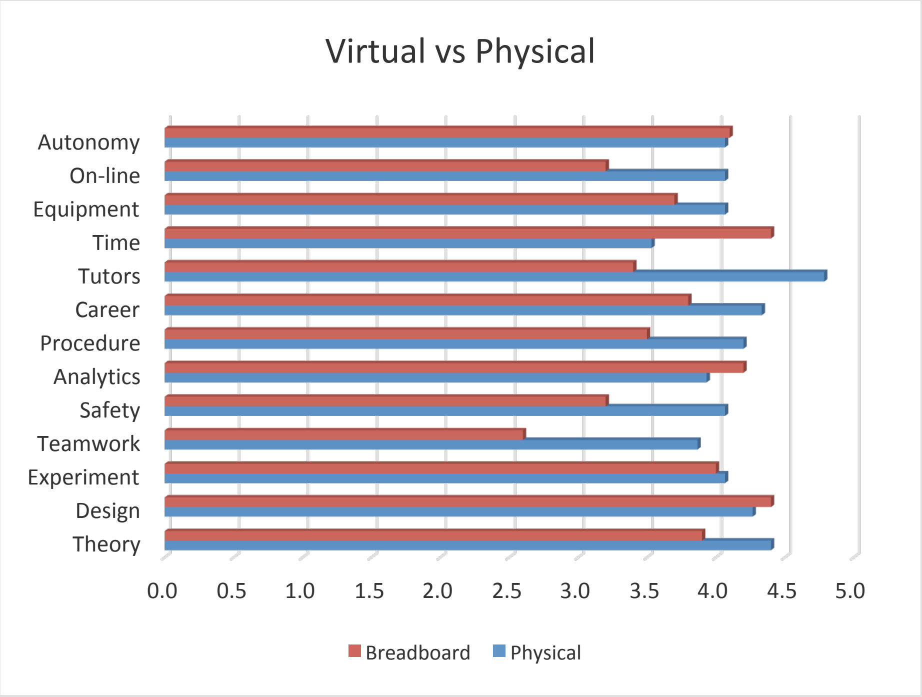


Figure 5-9 Physical Labs vs Breadboard Simulator in Post-Production Implementation Survey

Based on the sample averages, learning objectives of autonomy and experiment scores were very similar for the physical laboratory and the Breadboard simulator. The Breadboard simulator responses were clearly more positive on the issue of time, with small positive differences for analytics and design that are not statistically significant given the small sample size. Physical laboratories were much more positive on the categories of teamwork, safety, career, procedure and the availability of tutors. Note that the responses to online were measured using the following two questions:

- Physical laboratories: "*I prefer to go to labs and lectures rather than learn online*."
- Breadboard Simulator: "*I prefer online learning to lectures and labs*."

Responses tended to agree on the physical laboratories online question and were more neutral on the Breadboard Simulator version of the online question. The responses confirm that students see advantages of the simulator but do not appear to want to abandon physical laboratories.

Additional questions from the third survey provide more information on the students' preferences for using virtual laboratory equipment. When asked to rank the advantages of the Breadboard simulator, the responses indicated that "*more efficient use of time*" was the highest-ranking factor. The findings are shown in the following table with "1" being the most preferred.

Table 5-1 Advantages of the Breadboard Simulator

Advantage	**Average Rating**
More efficient use of time.	1.67
Looking at concepts from a different perspective	2.56
Developing critical and creative thinking skills.	3.5
Better understanding of the subject	3.5
Better understanding of lab equipment.	3.63
Developing teamwork skills	6

Students also ranked their preferred working style and the rankings are shown in the following table. On this question, the highest-ranking factor was using the simulator "*For revision before exam*", followed by "*On my own during my own time*."

Table 5-2 Working Style of Users of Breadboard

Working Style	**Average Rating**
For revision before exam	1.5
On my own during my own time	2.25
On my own during scheduled classes	3.38
In a group during scheduled classes	4.13
In a group during our own time	4.38
I prefer not to use such a tool	5.29

The interpretation of these survey results towards answering the research questions will be examined in the next chapter.

5.3 Faculty Interviews

Faculty interviews were performed beginning in 2016 after the Breadboard simulator tool was developed. Eleven experienced professors from UQ, Saudi Arabia (King Abdulaziz University) and Egypt (Al-Azhar University) were interviewed, primarily in face-to-face sessions. First, the professors were given a description of the nature and overall goal of the research. Then the professors were shown the tool and asked for opinions about enhancements that could be incorporated into the tool and their overall opinion of the tool. Once the open-ended discussions were completed, the faculty were then surveyed on the questions contained in the faculty survey (Appendix V) where four of the eleven professors completed the questionnaire.

During the face-to-face interviews, one professor expressed his belief that remote laboratory experiments are identical to experiments performed in the physical laboratory. If the equipment is real, students will gain the same knowledge and working with virtual laboratories makes experimentation free of risk. One professor felt that students should be exposed to virtual laboratories before attending a university, so they could explore different circuits and try different components. Another professor commented that “every teacher and tutor have a different opinion about virtual laboratories and their importance.”

The ABET learning objectives were the primary focus of the survey, with the professors asked to identify which objectives were considered the most important from their perspective. In addition, the faculty were asked about the advantages of virtual laboratories as a replacement for physical laboratories or as a supplement to physical laboratories. Other questions obtained their opinions on potential economic and organisational benefits, potential difficulties and aspects of assessing laboratory work. The findings from the interviews were entered in Survey Monkey while open-ended discussions were captured in written notes.

The summary of findings for faculty rankings on the important learning objectives is shown in Figure 5-10. The scores for each learning objective are calculated by multiplying the number of responses by the rank category (1-13) and then dividing by the number of responses. These values are then subtracted from the number of categories, so that higher scores indicate higher importance for the learning objective. For example, the design category score is 9.75, reflecting that the respondents ranked design higher than learning from failure (4.25).

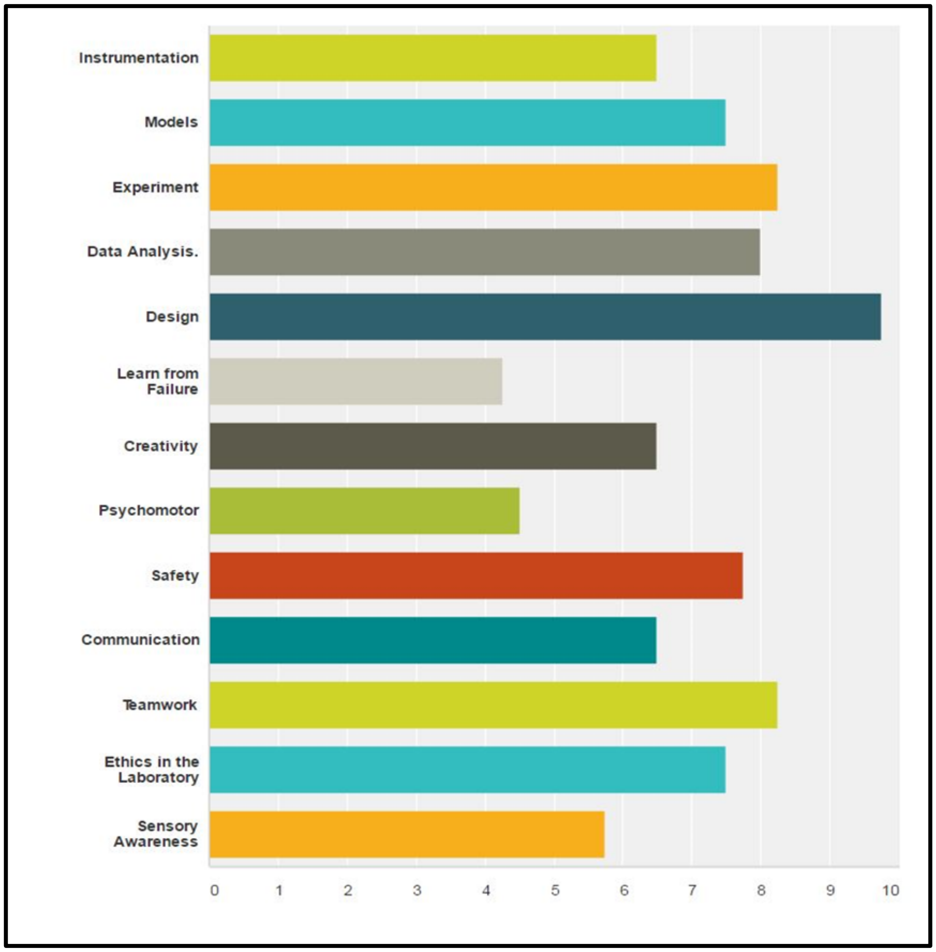


Figure 5-10 Important Learning Objectives from Faculty Perspective

Overall, the professors felt that design was the most important learning objective, followed by experimentation and teamwork. The objectives of learning from failure, psychomotor skills and sensory awareness were the lowest ranked in importance.

Besides the ranking of learning objectives, there were also a series of open-ended questions. The first open-ended question related to which learning objectives could be well-served by virtual laboratories. The responses include “Creativity” and “All of them”. One respondent felt that “Clear Instruction” could be an additional objective. The professors were in complete agreement that virtual laboratories would not serve as a replacement to physical laboratories, but as a supplement to them.

The next question related to identifying which learning objectives would be most difficult to be served by virtual laboratories. There were three respondents that all agreed that psychomotor skill and teamwork were the most difficult. One of the three respondents also include safety and sensory awareness as responses.

Regarding the potential economic and organisational benefits, the savings of time and money were identified by three respondents. One respondent felt that the size of the physical laboratory could be reduced as well. Difficulties in virtual laboratories were identified as acquiring skills and that simulations/software of some laboratories were not commercially available.

Finally, the last open-ended question related to what aspects of laboratory work should be assessed and how virtual laboratories could help with the assessment. One respondent felt that skills are difficult to gauge in the virtual laboratory and that the process of conducting the experiment should be assessed, not the data collected. The other respondent felt that assessment in the virtual laboratory would be like the physical laboratory, based on participation, simulation, analysis and uploading results.

6 Answers to Research Questions

In this section, the results from the previous chapters are discussed in the context of how the first three research questions are answered.

6.1 Answering Research Question 1

Research Question 1 – What is the relative capacity of virtual laboratories versus physical laboratories to enable the desired learning objectives of engineering laboratories, especially those viewed as important by students?

The 13 ABET objectives cover instrumentation, theoretical models, experimentation, analysis of data, design, learning from failures, creativity, psychomotor skills, HSE, communication, teamwork, ethical aspects and sensory awareness. In the literature, it was argued that students can learn as well in a virtual laboratory as they can in a physical laboratory [35], [39], [99], [102], that students are more motivated [39], that students can analyze instruments in detail [103], [104], that students can relate theoretical to practical [39], [85], [74], that experimentation is faster [105], that students have better focus on data analysis [103], [107], that students have better focus on design [107], that students learn from failures [106], that communication and data sharing is easier [83] and that virtual laboratories enhance teamwork [62], [72].

Realism was a common theme in the pre-survey open-ended responses. The concept of realism directly relates to ABET learning objectives of instrumentation, theoretical models, experimentation, design, psychomotor skills and sensory awareness. The respondents frequently mentioned chat, collaboration and feedback from the tutors in real time as important in a virtual laboratory. These aligned with the learning objectives derived from the literature including communication abilities and teamwork skills. Many respondents were interested in tutor feedback and software feedback that would provide the student with immediate correction in real-time. These items align with learning from failure as described in the ABET objectives, but highlight the impact of modern technology, in that students understand that more timely feedback on their errors can improve the quality of their learning.

The analysis of data was not mentioned in the survey responses as an important item but was mentioned in the literature as allowing students better focus by using a virtual laboratory [103], [107].

Items in the ABET objectives that were not mentioned in either the literature or in the survey responses were ethics and safety.

In the survey findings from the post-production implementation survey, students felt that use of time, analytics and design were better in the virtual laboratory as compared to the physical laboratory. These findings were consistent with the literature [103], [105], [107]. They also felt that teamwork, equipment, theory, safety, tutors, procedure and implications for their career were better served in the physical laboratory. These findings were not consistent with the literature, and this is likely because most literature related to the topics of physical laboratories and virtual laboratories tend to be biased towards favourable opinions of virtual laboratories.

Students that were surveyed felt that the learning objectives of autonomy and experimenting were about equal in the virtual laboratory and the physical laboratory, which is consistent with the literature findings [105].

The individual learning objectives in the ABET list can now be evaluated one-by-one as to the suitability of virtual laboratories for meeting these objectives.

Instrumentation. Even if virtual labs are designed to be as realistic as possible, the operation of instrumentation equipment, including correct connections of equipment to devices under test can only be simulated to a certain degree, so physical laboratories are superior for practicing the use of instrumentation. For virtual laboratories, the implication is that there should be an adequate degree of realism to give familiarity with the way in which "real" instruments work. However, one advantage for virtual laboratories is that mixed-mode simulations can add "virtual" instruments that are not possible in a real laboratory, e.g. by displaying magnetic field lines around conductors, or by displaying all circuit currents and voltages simultaneously.

Theoretical Models. The learning objective here is to reinforce that physical systems are modelled imperfectly by theoretical equations, and that measured quantities have limited precision and accuracy. Since a simulation laboratory uses such models to simulate the circuits, such imperfections and imprecision may be missing. Physical laboratories have an advantage in realising this learning objective since they are clearly measuring real components with real instruments. They meet the student need for a "realistic" laboratory experience. The implication for virtual laboratories is that the "imperfection" of real systems should be captured in the tool. Remote laboratories, which provide remote access to real systems can be more convincing, but it is also possible to incorporate imperfections into simulated components and instruments. Virtual laboratories do have the potential advantage that a greater range of virtual systems can be incorporated into experiments. For example, a simple current/voltage experiment could be extended to resistive loads such as bar heaters and light bulbs where device temperatures vary greatly, and more easily exhibit the non-linearity of Ohm's Law under such conditions.

Experimentation. The idea of this learning objective is to design and execute a set of scenarios, typically which expose some underlying physical phenomenon. For example, an experiment might measure the current through a resistor as the applied voltage is changed, and then identify the relationship between these quantities. Physical and virtual laboratories both have similar capabilities to allow such experimental design and execution.

Analysis of Data. Having undertaken an experiment and measured some quantities, the next stage is to analyse those results, perhaps to check their agreement with simplified theoretical models. In the case of physical laboratories, at least using simple equipment such as that in the experiments investigated in this thesis, measurements are typically noted in a lab notebook, then transcribed to spreadsheets or other analytical tools. Separate analysis of error bands for measurements might be added. With virtual laboratories, all of the circuit stimuli and measured values could be automatically captured during experimental execution, and the data analysis tools, including error analysis, could be built-in. Again, the use of "virtual" instruments could aid the process, e.g. rather than a voltage source being set to 5V, it could be set to step from 0V to 10V in 0.1V increments, and the resulting 101 currents recorded, and all the data loaded into analysis software. This learning objective is better served by virtual laboratories.

Design. Laboratories play an important role in the engineering design process. For example, before a new amplifier was manufactured, its circuit design would typically be tested and refined in the laboratory, with perhaps different circuit configurations tried. Experimentally-based design was the most important laboratory learning objective identified by faculty. The fact that many different design alternatives can be quickly trialled in a virtual laboratory, potentially using devices from a catalogue of hundreds of different components, means that virtual laboratories have a potential advantage in achieving this objective. Students who design flawed circuits that would damage real components and instruments can recover much more quickly in a virtual laboratory. In fact, if laboratories are used in preparation for professional engineering design, and since the great majority of electronic design today starts with very detailed and extensive simulation studies, virtual laboratories may even be more "realistic" than physical laboratories in such situations.

Learn from Failure. This learning objective teaches students to understand the reasons and consequences of unexpected results. Real circuits, for example, may give unexpected results because components are used incorrectly (e.g. a diode inserted back-to-front), because there is a fault in the component (eg. broken diode), because the component connections are faulty, or because the instrumentation devices are faulty. Being able to identify the source of the problem is a valuable skill that is needed in professional lab work. Physical laboratories are better preparation for later professional use of the same sorts of components and equipment. A simple simulation laboratory tool, such as the one trialled in this thesis, never has faulty instruments, circuit breadboards or components. If the simulation fails because of an Internet failure, or because the software crashes, that is hardly the sort of "learning from failure" intended. The implication for virtual laboratories is that extra design effort is needed in the tool if equipment and component failures need to also be simulated. On the positive side, such faults can be much more controllable, e.g. early labs might use "perfect" equipment, later labs in the same course might introduce planned faults.

Creativity. Virtual laboratories are superior here. A potentially vast catalogue of components, no risk of damaging equipment, and the round-the-clock availability of a virtual lab encourages students to explore new experiments beyond that needed to complete a fixed set of classroom exercises [115]. Although there is a movement towards universities and schools providing physical "makerspaces" explicitly for encouraging laboratory and workshop creativity, virtual laboratories naturally provide such a space.

Psychomotor skills. This refers to learning the physical actions to build and operate real equipment with real components. Here physical laboratories are clearly superior. The difference is something like learning to drive on a computer simulator versus learning in a real car. The importance of these skills will depend on the instructional domain. For electronic circuits measuring invisible and inaudible electricity psychomotor skills are less essential. There are skills associated with tasks like soldering components, attaching bayonet leads, and pushing wires into breadboards, and these are impractical to replicate with current technologies.

Health and Safety. For laboratories involving components with large momentum, dangerous voltages, or dangerous chemicals then an important component of lab work is to learn safe operating procedures to avoid the risk of danger to the student or the surrounding environment. This learning objective is better served by physical laboratories. It is not even clear how some of these issues could be convincingly incorporated into virtual laboratories. For example, asking students to put on lab coats and safety shoes before using a computer simulation seems nonsensical.

Communication. This learning objective centres around the idea that laboratory work involves reporting and explaining the results of experiments, through written and verbal reports. When written reports are produced after the experiment is completed, there is no particular difference in effectiveness, based on how the experiment was conducted. It could be possible that if a result seemed strange during report writing, a virtual laboratory would allow the experiment to be quickly repeated and the results verified. Communication in the laboratory experiment itself is dealt with in “teamwork” below.

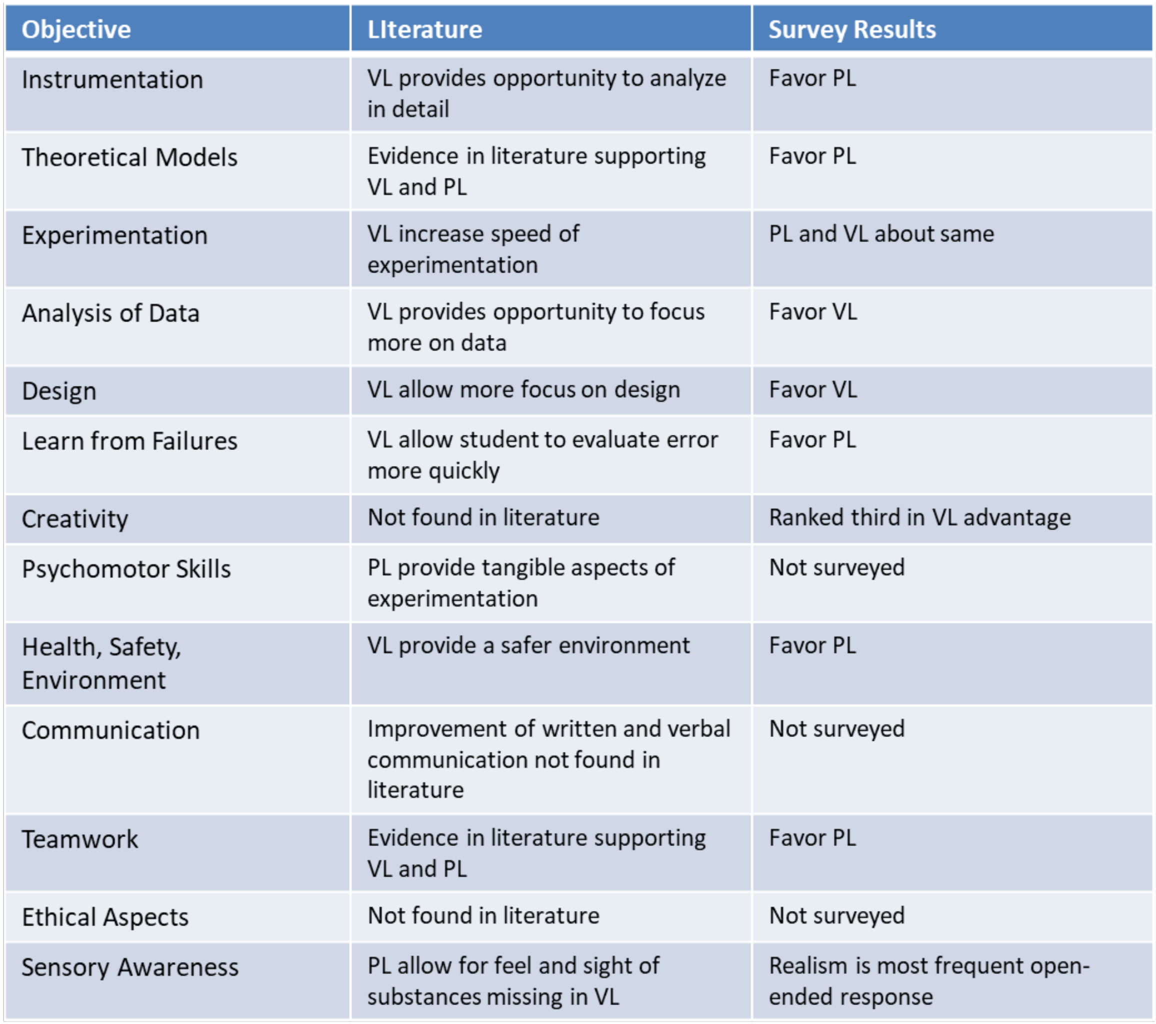
Teamwork. Working and learning in groups can be substantially richer than working alone. Having ready access to a lab tutor while conducting an experiment can also aid understanding. Such learning is much easier when learners and teachers are all together at the same time, in the same place, so physical laboratories are preferred. In the Pre-Design Survey, students showed a strong preference for doing laboratory work in scheduled classes, in groups, in order to learn from other members of the team. The strong implication for virtual laboratories is that if virtual laboratories are used alone (not as an adjunct to physical laboratories), then to be most effective they should allow group-based learning and access to tutors during the execution of the experiment. A chat room, frequently asked question (FAQ) or bulletin-board system is unlikely to be sufficient to replicate the physical laboratory learning experience.

Ethical Aspects. Ethical aspects deal with honestly recording and reporting laboratory experiments, since such behaviour would be expected from research publications and consultant reports later in engineering careers. There has been little discussion in the literature on incorporating this into laboratory experiments, as against the broader ethical aspects of tertiary education in general. There is no reason to expect that physical or virtual laboratories would make a difference to ethical behaviour. While it would be possible to check, using suitable learning analytics, that individual students had completed the experiment with the results claimed in their reports, this issue is not investigated further here.

Sensory Awareness. If psychomotor skills deal with the manual dexterity to manipulate and control instruments, sensory awareness uses sight, sound, touch and perhaps smell as part of the interpretation of what is happening when a system is suitable stimulated. For example, vibration may indicate whether a motor is running smoothly or not. This is better done in physical laboratories. Visual realism is a good goal for virtual laboratories, such as our simulated breadboard and meters. However, it is unclear whether adding realistic audio is useful, and touch and smell are beyond practical modern technology.

A summary of the findings is presented in Table 6-1 below.

Table 6-1 Most Important Learning Objectives



Objective	LIterature	Survey Results
Instrumentation	VL provides opportunity to analyze in detail	Favor PL
Theoretical Models	Evidence in literature supporting VL and PL	Favor PL
Experimentation	VL increase speed of experimentation	PL and VL about same
Analysis of Data	VL provides opportunity to focus more on data	Favor VL
Design	VL allow more focus on design	Favor VL
Learn from Failures	VL allow student to evaluate error more quickly	Favor PL
Creativity	Not found in literature	Ranked third in VL advantage
Psychomotor Skills	PL provide tangible aspects of experimentation	Not surveyed
Health, Safety, Environment	VL provide a safer environment	Favor PL
Communication	Improvement of written and verbal communication not found in literature	Not surveyed
Teamwork	Evidence in literature supporting VL and PL	Favor PL
Ethical Aspects	Not found in literature	Not surveyed
Sensory Awareness	PL allow for feel and sight of substances missing in VL	Realism is most frequent open-ended response

Students desire to learn the material in the short term, to achieve good scores on assignments and tests, and in the long term, to pursue and be successful in a career. These desires are somewhat in alignment with the opinions of faculty, who were also surveyed for input on important learning objectives. The highest ranked learning objective from the faculty perspective was design, and other important objectives were teamwork, experimentation, data analysis, safety, models and ethics. While learning from failure was important to students, this objective ranked the lowest from the perspective of faculty. Other low-ranking objectives were psychomotor skills and sensory awareness. The reason faculty would rate learning from failure the lowest is not clear, but the focus of faculty appears to be on the core skills for electrical engineering of design, experiment and data analysis. It may be that learning from failure, sensory awareness and psychomotor skills are perceived as being less in control of the instructor, and more a function of the personality and/or physical characteristics of the students. These insights around the suitability of virtual laboratories to implement different learning objectives will be examined again in the design guidelines.

6.2 Answering Research Question 2

Research Question 2 – Based on a trial virtual laboratory deployment, which design features of a virtual laboratory are important from student perspectives?

In the literature review in Chapter 2, user interface [46], [88], [72], realism [88], [14], [79], individualization [46], storage capacity [13], [88], social interaction [46], [89], [79], simplicity [88], multimedia features [58], [61], help features [14], [89] and qualified technical staff [61], [87] were identified as important design considerations in virtual laboratories. Features identified in the surveys were the user interface, realism, real-time tutors, chat, online help, system response to errors, speed and reliability, message consistency, visual clarity, knowledge sharing capabilities, and individualized and group scheduling.

The features identified in the surveys are consistent with the features identified as important in the literature, yet more comprehensive. The open-ended responses from the students in the pre-design survey included:

- *"Extremely user friendly – Obvious icons and methods of construction – Nice visuals/aesthetics."*
- *"Explanatory videos on what things do and how they work."*
- *"Simplicity. There would be no point in having access to the virtual labs if it is very difficult to use."*
- *"Having a variety of laboratory equipment and the ability to build circuits online. Would also help to have a simulation of the 1300 practical exam online!"*

Several of the respondents mentioned an ability to chat, and that feature would improve their collaboration and communication with tutors, team members and other students. Student responses included:

- *"Speed and reliability and collaboration with other students and fancy stuff is less important."*
- *"A chat system for communication within your group and with your respective tutors."*
- *"A real-time feedback or chat with a tutor."*
- *"Being able to ask tutors a question with a response given in less than 10 minutes."*
- *"If my lab experiment set up was wrong, I would like the software to indicate my mistake and provide a list of options on how to fix it."*

While social interaction is mentioned in the literature, real-time (or almost real-time) feedback and chat features are specific items mentioned by the students that do not appear in the literature. The use of error correction feedback was extremely important to the students as a design feature.

One aim of this research question was to understand if the features that are important to students are like those that were identified by designers in the literature review. Some new insights have been developed that were not apparent from the literature review.

Users do not want to use a software program with poor quality, so issues like ease of use, intuitive user interface responsiveness, and reliability are essential for any successful software implementation. Realism was seen as important from a student and designer perspective.

However, a new insight from students who had experienced a physical laboratory which is centred around active learning in small teams, with proactive tutor support, was the high value placed on communication with others in the laboratory setting. This is important in two settings. Firstly, there is a need to understand how to use unfamiliar laboratory equipment. In the physical laboratory, this is done by tutors first demonstrating the equipment use, and then tutors being readily available to help as students start using the equipment themselves. Secondly, there is a need to understand the theoretical concepts that are being practically demonstrated in the laboratory. In the physical laboratory, this is done by communications within the group and regular requests from tutors for students to explain their understanding.

These different forms of interaction are difficult to replicate in a virtual laboratory setting. The equipment demonstration aspect is relatively easy. In the ENGG1300 course, short videos are used to demonstrate key computational techniques (such as calculating circuit currents and voltages), so the student request for videos can be seen more generally as a request to replicate the explanatory demonstrations in the physical laboratories. In the breadboard simulator developed in this laboratory, this was done with on-line "how-to" guides, acknowledging that students understood the general operation of equipment from physical laboratories. Videos, or guided animated demonstrations could achieve this in virtual laboratories.

Another venue of communication with tutors is to provide help when students run into difficulty. This is difficult to achieve with a virtual laboratory tool that can be used 24/7. It would require both the availability of tutors round the clock, and it would require screens to be able to be shared, and perhaps real-time audio communications. This is all possible, but certainly not simple with today's technology. Advances in artificial intelligence could soon give the possibility of "virtual" tutors to help with the first level problems that students have. As students noted, at the very least, very detailed explanations of experimental errors are needed, so that in the absence of real-time tutor support, students can fix most problems themselves.

The most difficult area is enabling groupwork. One advantage of virtual laboratories is that students have some flexibility in their working style. As indicated by the surveys, students prefer groupwork, but there are some students who prefer to work alone. Virtual laboratories potentially provide support for these different modes. Students can work alone, at their own time and pace. With appropriate tool support, students in an existing group could schedule a time to work together via on-line communications. Finally, with even more tool support, ad-hoc groups could be formed from sets of students currently on-line. Whatever the situation, one key insight which will be addressed again in the design guidelines presented later will be this need to address the social and communications aspects that are known to work well in physical laboratories.

6.3 Answering Research Question 3

Research Question 3 – What are the advantages and disadvantages of virtual laboratories as a supplement to physical laboratories compared to serving as a replacement for physical laboratories?

In the literature, faculty and student evaluations of virtual laboratories were mixed. Some students felt that computer experiences were not capable of replacing the physical laboratory experience and argued that computer screens are not capable of replacing many laboratory instruments. Collaboration in online environments was found to be frustrating for some students, but others felt their teamwork skills improved. Studies found that students find physical laboratories easier and more satisfying than virtual laboratories and that virtual laboratories are integral to traditional laboratories, but not a replacement.

Several studies in the literature advocated that the learning outcomes obtained in virtual laboratories are comparable to the outcomes obtained in the physical laboratory and for disabled students, and students in remote or rural areas, access to laboratories is now a reality. Educational leaders found it increasingly important to provide online learning, while for faculty, generating the exercises was found to be more burdensome. Again, the literature was somewhat mixed in that monitoring of students was found to be more difficult in one study, but others found that virtual laboratories improved the monitoring of students.

In the pre-survey results, realism was the most important consideration of the respondents, and indicates that a virtual laboratory should provide an experience that gives them the same capabilities that they have in the virtual laboratory. In the open-ended responses regarding the virtual laboratory, comments related to the topic of realism included:

- *"For it to feel as real as possible such that it is almost identical to the real thing. Otherwise I feel the necessary physical skills will not be developed."*
- *"To be able to operate the equipment as if they were real. In other words, not just use clicks from the mouse to complete the whole work."*
- *"An interface as similar to the real thing as possible – knowledge be transferrable."*

From these and other comments, the students sought experimental realism so that their experience in the virtual laboratory is comparable to their experience in the physical laboratory and that the skills developed are transferrable to a real-world setting. The ability of a virtual laboratory to supplement physical laboratories appears to be highly dependent on the concept of realism.

Around 7% of the respondents indicated that they were more interested in using a physical laboratory as opposed to any virtual laboratory. While overall, most respondents were excited about using the simulator, it is important to note that there is a contingent of the student population that prefers the experience in the physical laboratory. Some of the student responses were quite adamant about their desire to work in a physical laboratory, including the following:

- *"I would not want to use virtual laboratories. I am paying to learn how to use equipment in the real world. It is of no use to me if I am using a virtualization of a physical device, if I have not understanding of how it works in the real world."*
- *"Laboratories need to be in real life, stop trying to make university online."*
- *"Accessing physical equipment via web interface is not how I would want to learn. From an industry standpoint, I would assume that all work is done locally (as opposed to remotely) unless circumstances prevent it, i.e. needing expertise at a remote location or in a hazardous location. And this is with someone who is already trained and experienced in the field."*

The student in the last comment brings up areas where virtual laboratories are highly relevant – in the cases of hazardous circumstances or where the real-world application of the skills require use of a virtual or remote operation of equipment.

From the comparison survey of virtual laboratories to the Breadboard simulator, it was found that students were using the Breadboard in timeframes associated with exams and rated using the Breadboard prior to an exam as the highest-ranking working style. Efficient use of time was the highest-ranking advantage. Some students found a very effective use of the tool by confirming physical laboratory work using the simulator prior to testing. The online setting provided the additional time to work and rework exercises.

Twelve faculty members in the Electrical Engineering and Information Technology departments at UQ were also surveyed to find out whether they saw virtual laboratories as a replacement or a supplement to physical laboratories. Instructors were selected based on the requirement that they participated in instructing the Introduction to Electrical Systems course (ENGG1300). The respondents unanimously felt that virtual laboratories were a supplement and not a replacement.

The results from the surveys fail to indicate that virtual laboratories can completely replace physical laboratories. The results do indicate that students find positive uses for both environments. While collaboration and teamwork may be enhanced in the physical laboratory, use of time, design and autonomy appear to be strengths of virtual laboratories. Experimentation, design, theory and equipment categories were rated somewhat similarly between virtual laboratories and the Breadboard simulator indicating that there are some learning objectives that can be met using either method. The survey results from the post-production implementation survey indicated a weakness of the Breadboard simulator compared to physical laboratories regarding tutors, and students recommended that real-time feedback from online tutors would enhance their usage of virtual laboratories. In addition, even the students that preferred the use of a physical laboratory recognize that there are needs for virtual and remote laboratories to acquire the skills necessary in real-world situations where operation of equipment may need to be performed remotely.

Therefore, it is a strong recommendation from this work that virtual laboratories, at their current level of sophistication, are most useful as an adjunct to physical laboratories, not as a replacement. The design guidelines in the next chapter will address this issue also.

6.4 Summary

This chapter has provided answers to the first three research questions. These answers are preliminary steps towards the development of the comprehensive set of design guidelines to be presented in the next chapter, and which bring together the research threads of this thesis.

7 Design Guidelines

In this chapter, the comprehensive list of design guidelines is presented along with a framework for undertaking development of a virtual laboratory. This chapter addresses the following research question:

Research Question 4 – Given the experiences in this trial deployment as well as insights from other virtual laboratory deployments, what is a useful set of design guidelines for virtual engineering laboratories?

7.1 Process for Guideline Development

These guidelines were developed using several sources. Personal experience by the author in specifying, designing, implementing and deploying the prototype tool has enabled a number of issues to be identified. Although these issues have occurred in the development of one particular tool for one particular course, many of these issues are likely to be relevant to many different tool deployment scenarios.

Secondly, the literature review has surveyed a wide range of papers, many of which have highlighted particular issues in those deployments. This research can usefully inform the design of these guidelines.

Thirdly, the work on RQ1 has explicitly investigated what a suitable set of learning objectives for laboratories are, and the analysis in Section 6.2 above has highlighted that virtual laboratories are not equally suitable for all of these learning objectives. Of course any single laboratory, or even all the laboratories associated with one course may not address all of these learning objectives. However, the literature review has not shown that learning objectives are often explicitly considered upfront in virtual laboratory design.

Fourthly, RQ2 in Section 6.3 above summarises the feedback received from student users of the prototype tool, to provide student input to the virtual laboratory design. This has two implications for the design guidelines. It identifies issues that are important to users of the virtual laboratory, and it also demonstrates that seeking such feedback as part of a participatory design process can improve the tool design. The work from this one deployment is combined with broader insights from users of other systems reported in the literature

Fifthly, RQ3 suggests that current virtual laboratory tools may not yet be ready to complexly replace physical labs, and this issue also should be considered within the guidelines.

Finally, the design guidelines include insights from modern software design and from modern learning management systems and other educational software design. The design guidelines here particularly highlight issues that were of high importance to users of this trial and other reported deployments.

One potential limitation of this work is that it considers in detail the deployment of one particular tool to one particular group of students in one course. To partly overcome this limitation, the guidelines also consider insights that have been reported by others in the literature. The guidelines have been constructed to highlight issues that are likely to affect the design of many different tools.

7.2 Guidelines Around Communications

A clear area that was important to students in our trial that has been highlighted in other deployments and is consistent with the general laboratory experience, is that the laboratory experience is a very social experience with rich interpersonal communications. Students can discuss with their group members, and they can get help from teaching staff as soon as they encounter problems with the use of the equipment, or with theoretical understanding. Virtual labs provide a more disconnected social experience and these first guidelines look at how at least part of the richness of the physical laboratory can be supported.

The students mentioned in the surveys that their favored learning style is to work in a group during classes. The interaction with other students and tutors while participating in groups enables them to share information and knowledge, which in turn helps them to better understand the subject. Comparing their internal understanding and views with those of their peers and tutors, who may have different perspectives, broadens their grasp of the learning material. Communication and teamwork are both ABET learning objectives, and the group interaction helps the students develop deep links between what was discussed in the classroom and discovered in the laboratory. The ability to communicate and work in groups are skill sets that engineers need when working on real-world problems, and sharpening these skills help them deal with projects and problems that they will encounter during their careers.

Getting real-time feedback and developing critical thinking were also important to students who responded to the initial survey. Real-time feedback is a critical component of sharing information that enhances the students' learning process. Learning from failures is an important ABET learning objective as well, and students indicated early in the design process that responses to errors needed improvement in the prototype simulator, further indicating how much they value feedback. Real-time feedback on the errors made during an experiment allows the student to immediately process what mistakes they have made and how to correct them. In addition, the amount of access time in the physical laboratory combined with course load and scheduling concerns can result in a sense of urgency for the student to complete assignments and prepare for testing. Not every experiment can be completed perfectly on the first try, and to get the right results or redo an experiment during a fixed laboratory schedule further drives a desire to have prompt feedback from either the tutor or their peers.

There are several options for implementing knowledge sharing capabilities and real-time feedback in a virtual laboratory. Features like chat rooms for group discussion are available 24 hours per day for students working remotely, and can include feedback from tutors. While constantly available, there can be delays between postings and responses, which does not totally replicate the experience of working with other students in the physical laboratory during a scheduled class period.

Real-time feedback of errors such as incorrect circuit configurations was implemented in the Breadboard simulator developed during this research, allowing for real-time identification of some errors, but other feedback, such as answers to "Why doesn't this work?" currently require online tutor support, at least until artificial intelligence engines are sufficiently advanced. Providing 24/7 real-time support is cost-prohibitive in a university setting, but providing support during scheduled hours, similar to "office hours" would be reasonable. This leads to the first design guideline:

Design Guideline 1 – Enable sharing of knowledge and real-time feedback.

Student populations are diverse and consist of full-time students, part-time students, students with jobs, older students and students with families, as well as students with special needs and/or disabilities. Working students, especially international students may take low paying, late night jobs to pay their university fees, rent and expense, that can in turn make it difficult to attend sessions in the physical laboratory. Even illness or an unfortunate accident, like a broken leg can put a student's standing in class in jeopardy. Around one-third of the students surveyed did prefer working on their own time and could be supported by enabling options for individualized learning and group scheduling.

Individualized learning is important for students that have different learning styles and is helpful for students with disabilities and perhaps students with language barriers. Providing this capability through a virtual laboratory means offering flexible scheduling and perhaps additional time to complete assignments or modified assignments, as well as possibly offering tips and features for language translation. Regardless of whether individualization is offered in the physical laboratory or the virtual laboratory, there may be additional preparation and development of assignments for students that require individualized instruction.

Integrating the tool with an LMS can make the tool better for both students and teachers and can help improve communication skills, an important ABET learning objective. For example, the teacher can track what students are doing, how they are using the tool and at what times students are accessing the tool. Students can access the tool easily by clicking on a link from the LMS. By offering group scheduling, through chat features by text, audio and/or video formats, the remote classroom can be integrated with the physical classroom, allowing maximum access to students who may be physically distant from the university or physically unable to attend on-campus class settings. Providing virtual groups would help students catch up and stay current in coursework, encouraging each other to work and study harder. This leads to the second guideline:

Design Guideline 2 – Enable options for individualized learning and group scheduling.

A key learning objective in the ABET list is the ability to learn from failures. For most students, more than one attempt will be required to successfully complete an experiment, and the process of turning a failed experiment into a successful experiment means the cause of the failure needs to be identified. Error messages from the virtual laboratory are key aspects of identifying failures and providing information back to the user that assists them in correcting the error and learning from the error.

This guideline contains two key words – consistent and useful. Consistent responses are responses that are not only the same message given identical conditions, but are consistent across messages in the use of terminology and the structure of the message. When using a system, there is usually some time required to become familiar with the way the system works. Understanding how a system works, leads to efficiencies when using a system, and these efficiencies are improved when responses from the system are reliable and consistent. Inconsistent messages can lead to confusion and possible frustration from the users, as the users are building a conceptual framework of how the system "usually" responds and what the system "usually" means when messages are displayed.

Useful messages are also important. There is nothing more frustrating that to receive a message back from the system that provides no value, or worse, is misleading in its responses. Early in the design process for the Breadboard simulator, students identified useful and consistent messages as important, understanding the importance of these messages to their success in using the virtual laboratory. This leads to the third guideline:

Design Guideline 3 – Provide consistent and useful responses to errors.

Tutors and instructors are integral to the education of students. Tutors provide instruction for the coursework, answer questions and seek to impart their knowledge about the subject to the students in an effective manner. When students struggle with concepts, the tutors provide individualized instruction and assistance and often present the material in alternate formats so that students who learn differently can also learn the material. Students recognize the importance of tutors and identified tutor feedback as the second-highest feature they would want in a virtual laboratory (the highest rated feature was realism).

Tutoring is related to most of the learning objectives in some way. From the objective of learning how to use the instruments, to building and understanding theoretical models, to developing skills in data analysis and design, students rely on their tutors to enable their learning. Ethical considerations and health and safety issues are concepts that tutors cover, that provide life-long impact for students in their classwork and future careers.

Students identified specifically in the open-ended responses that real-time feedback was preferable. While this may not always be practical, it is understandable that students would like to have questions answered while the problem is current. Students generally juggle multiple classes, or classes and family and/or a job, and a delayed response from the tutor on an issue requires overhead on the part of the student to return to the problem that they may have put aside while waiting on a response. Providing online tutors during "office hours" is one method that can be implemented in the virtual laboratory to closely approximate real-time tutors. This leads to guideline 4:

Design Guideline 4 – Provide access to tutors, preferably in real-time.

One of the advantages of working in a virtual laboratory is the ability to take more time with experiments than what may be available in the physical laboratory. A disadvantage of working online is the inaccessibility of a tutor. Students would ideally like their tutors to be available 24/7 to answer questions in real-time, so that if they are working on an exercise after putting the children to sleep, or after working a job, or after finishing other assignments in the middle of the night, the assistance is a click away. While this may be ideal, it may not be practical.

Online help, such as tutorials and videos all for self-help and were identified in the literature and the surveys as useful features for virtual laboratories. Tutorials provide the step-by-step guidance for working experiments and can be staggered in such a way that they work from simple concepts to more complex. Tutorials can not only be provided for help with experiments, but they can also be provided for new users of computing equipment and overall usage of the different features provided by the virtual laboratory. Videos are extremely helpful in addition to tutorials, because they provide an audio and visual guidance of the experiment process. When a concept is not understood, the video can be rewound many times to allow students to review, in detail, the portions of a process that they may be struggling with.

Online tutorials and videos can be tailored to focus on specific learning objectives, such as building theoretical models, analyzing data, and performing experiments. They also provide a forum for supplementary information for the course that may not be covered directly in the lectures. For students with time constraints, or particular struggles with specific concepts in a course, online materials can not only enhance the virtual laboratory, but many aspects of a course. This gives the fifth guideline:

Design Guideline 5 – Provide additional online help in the form of tutorials and/or videos.

7.3 Guidelines Around Laboratory Design

This next set of guidelines are based around what the purpose of the virtual laboratory is, in terms of the overall learning objectives of a course or program.

Realism was repeatedly identified in the literature as an important feature in virtual laboratories and was identified as the most important feature for students in a virtual laboratory from the open-ended responses to the survey. Realism refers to the ability of the virtual laboratory to accurately represent the physical laboratory, which in turn is designed to accurately represent real-world scenarios. Flight simulators and driving simulators are designed to give users training in situations that are close to reality as possible, with features and controls that are as similar as possible to the features and controls that are encountered when operating an airplane or driving a vehicle. Similarly, for electrical engineering students, they desire to have an environment, including the features and controls that are as similar as possible to the physical laboratory and the situations that they will encounter once they graduate.

Realism is closely tied to the learning objectives of instrumentation, experimentation and design, and to some extent sensory awareness and psychomotor skills. The virtual laboratory should provide students with the ability to use instruments and sensors, design a product or system and be able to experiment with the system. If the virtual laboratory environment does not provide realism, in the sense that the instrumentation appears and operates in a similar fashion to the physical instruments, the value of the virtual laboratory is eroded for the student. For students that are reliant on remote systems for their education, realism is imperative as the virtual laboratory is their source of skill development in using the instruments, designing and experimenting with the instruments. For students that have access to both the virtual laboratory and the physical laboratory, realism provides them the ability to supplement their work in the laboratory seamlessly with the work performed outside the physical laboratory. Using the virtual laboratory to prepare for classwork and testing has been found useful for students, and a more realistic environment makes it more likely they will use the system and that their use of the system is more effective for their short-term goals as well as their career goals.

Providing realism in the virtual laboratory requires an understanding of multiple facets of the physical laboratory. What are the instruments and how do they work? What are the inputs to and the responses from the equipment? Proper scaling and options need to be designed into the virtual laboratory so that when using the system, it closely resembles the physical laboratory. In this research, a prototype system was an initial step to allow students to experiment with the virtual laboratory and provide feedback for design improvements. This approach was highly successful and is therefore recommended and appears as the next guideline.

Design Guideline 6 – Provide realism in the system.

For some students, they felt that it may be detrimental to their future careers if all their educational experience is conducted virtually, with no time spent in a physical laboratory. This concern was expressed by several students in their survey comments, while at the same time other students acknowledged the need to be familiar with newer virtual technologies that are increasingly being adopted by their future employers. Students want to feel the same experience in the virtual laboratory as they have in the physical laboratory and ideally have experiences from both. For distance education students, work in the physical laboratory may not be an option while on-campus students have the availability of both the virtual laboratory and the physical laboratory.

For mastering coursework, the virtual laboratory provides the additional time that many students need to repeat experiments, prepare for upcoming assignments and to prepare for exams. Coordination of the experiments in the physical laboratory with the experiments available in the virtual laboratory could greatly enhance the learning experience for students, allowing them to develop their skills in instrumentation, experimentation, design and other ABET learning objectives. One goal would be to provide the distance learning students with a learning experience that closely resembles the learning experiences available to on-campus students.

This level of coordination relies on commitment by the faculty and the tutors to ensure that the virtual laboratory and the physical laboratory assignments and capabilities complement each other. Synchronizing the environments could require additional time and training for faculty, and a willingness to utilize the best of both. Keeping abreast of new technologies and how they can be best used to improve virtual laboratories would be another area of responsibility for faculty, tutors and the technical staff at the university. This gives the next guideline:

Design Guideline 7 – Ensure that the virtual laboratory supports learning in the physical laboratory.

Including reference groups of students in the initial design process proved to be a contributing factor to the success of the project and to the use and acceptance of the virtual tool. Involving students in the initial specifications, user interface design, collaboration features, tutorial features and responses to errors substantially improved the design of the tool, while providing feedback that guided the design to focus on important and useful features.

Obtaining feedback from students was not difficult and students tended to be very open about their concerns and the features they were most interested in. The diversity of the student population in terms of computing background, electrical engineering background and language can directly affect design decisions. For example, the use of commonly accepted symbols to aid in overcoming language barriers may be necessary with a language-diverse population. Users that are novices in computing may require additional help features that are not needed by the computer savvy. Students that are primarily remote may need additional collaboration capabilities. The early discussions with students and using a prototype to foster the open communication of student wish-lists both engaged the students and allowed for the design to be better customized to the target student population. This leads to the eighth guideline:

Design Guideline 8 – Involve students in the design from the beginning.

At the core of providing a virtual laboratory is the essential capability for students to be able to learn and develop experiments. Virtual laboratories can be designed for a variety of academic areas and within the field of electrical engineering, there are many types of functionality that can be provided. For the Breadboard simulator, this functionality included the ability to design electronic circuits, the ability to connect the power supply, resistors, diodes and other components, simulate currents and voltages, and work with real equipment. Other useful features in a system would be the capability for students to zoom in and out using a good camera, the ability to create multiple versions of experiments, edit and share experiments and even created experiments that could not be performed in a physical laboratory. The functionality that was provided with the Breadboard simulator was designed to be closely aligned with the course objectives.

The ability to experiment is a key learning objective identified in the ABET list. It relates to students being able to design an experiment, as well as conduct the experiment and interpret and analyze the results. Therefore, this design guideline should be implemented early in the conceptual development of a virtual laboratory. Issues to be considered include the following. What academic departments will the virtual laboratory serve? Which courses will utilize the virtual laboratory? What experiments and learning objectives are contained in these courses? Will all experiments utilize the virtual laboratory? What changes are expected in the short-term and long-term goals of the relevant academic programs? Answering these questions helps to synchronize the virtual laboratory with the academic learning objectives and lays the groundwork for more detailed design decisions such as system architecture, user interface and supplemental features, such as chat and groupwork capabilities.

This design guideline requires input from faculty and educational planners in conjunction with input from the students to align the learning objectives and experiments with the academic goals from the program perspective and the student perspective. In addition, input from technical specialists is necessary to identify what can be accomplished practically given technology, resource and budget constraints.

It was shown in the discussion around RQ1 that it is rare for the learning objectives of a particular laboratory to be considered in detail. Such explicit consideration of the learning objectives of a virtual laboratory are largely missing from those laboratory deployments reported in the literature. It often seems to be assumed that the learning objectives of a physical laboratory are clear, and that the goal of a virtual laboratory is to replicate the physical laboratory experience, and so achieve those same learning objectives. Instead, the previous analysis in Section 6.2 above shows that virtual laboratories have different capabilities to achieve learning objectives. This gives the next guideline:

Design Guideline 9 – Explicitly consider the desired learning objectives in the virtual laboratory design.

7.4 Guidelines Around Tool Design

Students are now accustomed to sophisticated software programs with intuitive interfaces that are reliable and responsive. The following guidelines apply to almost any software system but are included here to emphasize the importance that well-designed and well-written software has to the overall satisfaction of learners, and their willingness to use these tools.

Students come to the university setting with differing levels of computer fluency and universities generally consist of a diverse student body. First year students may be enrolled in electrical engineering classes yet have no experience in a laboratory setting. The user interface to a virtual laboratory can operate seamlessly or can be a hindrance to students progressing, and a poorly designed user interface can cause frustration resulting in any number of undesirable consequences, such as refusal to use the tool, dropping out of a course, or poor performance on exercises.

Students usually have a high degree of experience with apps on their smart phones, tablets and desktop computers, and they usually do not expect to have to read a manual to understand how to use the app – they expect the app to guide them in its use until they are proficient. They will now expect the same quality of user interface in a virtual laboratory environment.

An intuitive and simple interface was frequently cited in the literature as important, and this was supported by student comments in the surveys, where they stressed the importance of an easy-to-use system that did not need to be fancy or filled with complicated features. Indeed, a simple interface was cited as being desirable to many of the survey respondents. The ABET learning objectives include the ability to use instruments, conduct experiments, and show creativity and design skills, and in a virtual laboratory the user interface to the tool is the "door" to being able to access the tools where students can develop and meet these learning objectives. Students also identified visual clarity as an important component of the user interface. Visual clarity can impact the ability of students to process the information that they see, affecting their performance in an exercise.

A good recommendation for a user interface design, is to allow students to have options for using the tool, in either the Breadboard or schematic view for the same experiments or circuits. The user can design circuits in one tool, for example on the Breadboard page, and when this is completed, the user can click see the corresponding schematic view. Linking the user interface to the experiments that will be performed in the classroom is also important, as students indicated in their feedback that they often like to discover an experiment before coming to the physical laboratory, so they have an idea of what to expect in the exercise during class. For example, adding a component to a virtual circuit could replicate the experience on inserting a physical component into a physical breadboard. This leads to the next guideline:

Design Guideline 10 – Provide a user interface that is intuitive, simple and easy to use, as well as easy to learn.

Speed of the system refers to the responsiveness of the system to user input. Reliability refers to the ability of the system to be available consistently and to provide consistent results to user inputs. If the system crashes repeatedly, students will not choose to use it if they have other options. If the tool lets a student down from its first use, or if their first experience with the tool is not good, they may not even test it again. If there are long delays in processing user inputs, the exercises can become frustrating as the user waits for results.

The survey results for the tool developed in this research indicated that for this simple circuit simulation there were no issues with the speed or reliability. Students got their results in a second, giving them confidence in the virtual laboratory. Most of the students wanted to use the virtual laboratory before the final practical exams, believing that the virtual laboratory would increase their performance and result in higher scores on their exams.

An important driver for speed and reliability is adequate testing in multiple conditions for the virtual laboratory toolset. There are multiple points of failure including the database, network, server(s), software, and internet speed. Incompatibilities, as well as reliability and speed issues can appear depending on browsers and other background software and applications, as well as any additional loads from other applications running on servers. The development and testing environments need to simulate the production environment, and a wide variety of testing should be conducted to maintain the expected performance.

Design Guideline 11 – Provide for speed and reliability of the system.

7.5 Implementation Framework

In addition to the above list of guidelines, a framework for implementation is provided in Figure 7-1 as a flowchart to show the list of steps and considerations that are important when embarking on a virtual laboratory implementation.

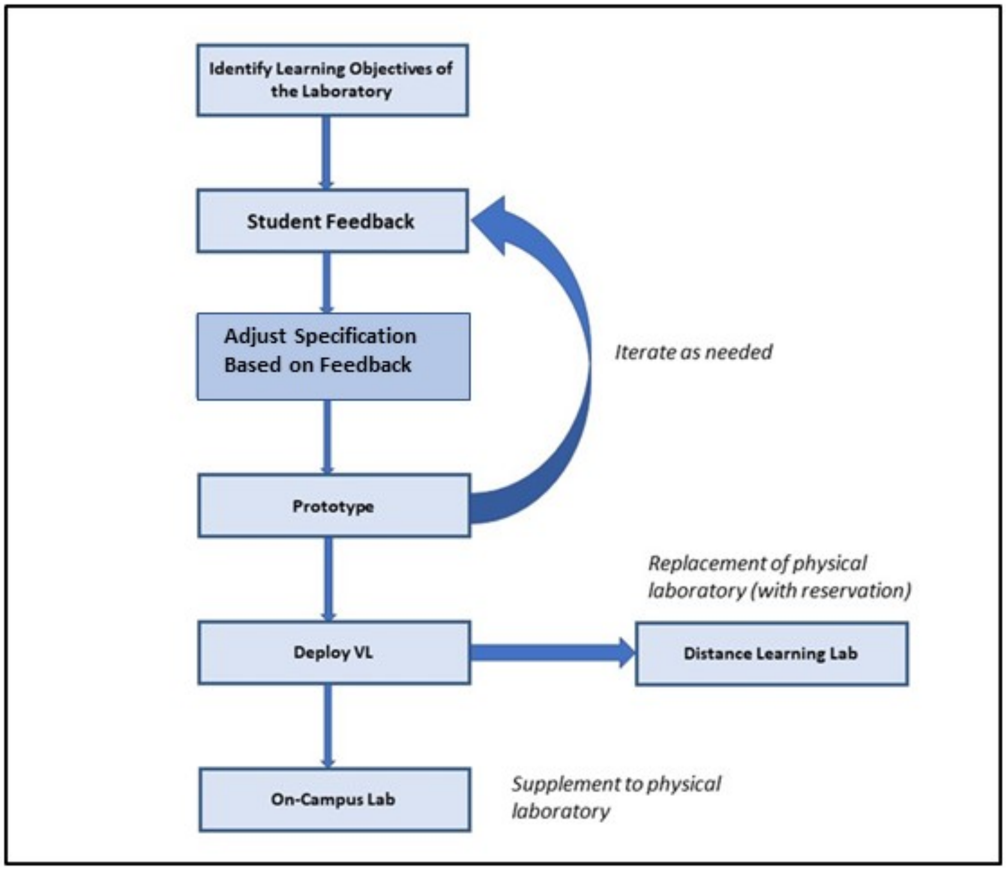


Figure 7-1 Proposed Virtual Laboratory Implementation Framework

The first step in the implementation is to identify the learning objectives of the virtual laboratory. In this step, consideration should be given to the purpose of the laboratory, in terms of the area of study and the types of experiments that will be performed.

In the next step, student input should be obtained. With this information, decisions can then be made about how the tool can be modified based on user input and what student suggestions can be realistically incorporated into the design. Is the laboratory going to be used for distance-only learners? If so, there may need to be more focus on the scheduling of groupwork, real-time tutoring and feedback options, and other features for online collaboration, particularly when distance-learning students are expected to perform in groups.

For virtual laboratory implementations where a physical laboratory exists, the implementation may be used as a supplemental laboratory only. This can impact the types of features that are implemented. The preceding steps may require iterations until the desired features are designed, implemented and tested successfully, and then the initial deployment is possible.

8 Conclusions and Future Work

This chapter firstly summarises the answers to the research questions that were posed in Chapter 3, then describes the significant, original contributions to knowledge in Section 8.2, mentions how some possible limitations of this work were overcome in Section 8.3, and gives some possible directions for future work in Section 8.4.

8.1 Summary of Answers to Research Questions

To answer Research Question 1, The most important learning objectives for students were ***teamwork*** and ***learning from failures***. The least referenced learning objective from the ABET list in both the literature and the surveys was ***ethics***, but should not be interpreted as the least important, perhaps it is just the least discussed. An important outcome from RQ1 is the fact that virtual laboratories may be better than physical laboratories for some learning objectives (e.g. analysis of data), but not as good for others (such as safety). These findings led to design guidelines 1, 2, and 3 in the list of design guidelines.

To answer Research Question 2, both the literature review and the survey results were consistent in finding that virtual laboratories need to provide ***realism*** for students to meet their learning objectives. Beyond what is currently in the literature, it was also found that not only do students prefer the availability of online tools for communicating with their tutors, they would prefer that ***the interaction be in real-time***. Both real-time interaction with tutors and real-time corrections to mistakes were important to students. These findings led to design guidelines 4, 5, 6, 10 and 11 in the list of guidelines.

To answer Research Question 3, student feedback was also useful. One new finding in this research was that the ***students preferred to use the virtual laboratory to prepare for examinations***, which is consistent with concerns regarding time management. Students may not have sufficient time in the physical laboratory to master the concepts being presented or may have difficulties scheduling laboratory-based classes due to institutional resource constraints. Another important finding, suggested by the students, was ***the need for virtual laboratories to prepare them for real-world situations where virtual or remote skills are necessary***. As technology has improved, engineers have more opportunities to respond to hazardous, or otherwise dangerous settings by using virtual and remote tools. Students were very interested in being prepared for real-world situations and the university education should prepare them for the use of virtual and remote tools as well as the physical equipment. A key outcome of the analysis of the current state of virtual laboratory design, is that a preferred stepping stone to more widespread adoption of virtual laboratories is to start with virtual laboratories as an adjunct to physical laboratories, so the technology can grow in maturity and some of the initial shortcomings of virtual laboratories can be solved by complementary activities in physical laboratories. These findings led to design guidelines 7, 8 and 9 in the list of guidelines below.

To answer Research Question 4, a comprehensive list of design guidelines was developed by incorporating findings in the literature and survey results. A list of eleven design guidelines was presented along with an implementation framework and are listed below:

- **Design Guideline 1 – Enable sharing of knowledge and real-time feedback.**
- **Design Guideline 2 – Enable options for individualized learning and group scheduling.**
- **Design Guideline 3 – Provide consistent and useful responses to errors.**
- **Design Guideline 4 – Provide access to tutors, preferably in real-time.**
- **Design Guideline 5 – Provide additional online help, in the form of tutorials and/or videos.**
- **Design Guideline 6 – Provide realism in the system.**
- **Design Guideline 7 – Ensure that the virtual laboratory supports learning in the physical laboratory.**
- **Design Guideline 8 - Involve students in the design from the beginning.**
- **Design Guideline 9 – Explicitly consider the desired learning objectives in the virtual laboratory design.**
- **Design Guideline 10 – Provide a user interface that is intuitive, simple and easy to use, as well as easy to learn.**
- **Design Guideline 11 – Provide for speed and reliability of the system.**

From this research, it would be difficult to argue that virtual laboratories can always completely replace physical laboratories, but the students were found to be effective at using the virtual laboratory to improve their learning and supplement their learnings to perform better on their tests. They also point out the need to learn how to develop skills using remote and virtual environments that are currently necessary in real-world environments (for example, hazardous situations).

8.2 Contribution

Descriptions of virtual laboratories have been described in the literature in previous research, but there has not been a discussion of learning objectives and their importance to the design of a laboratory. Indeed, rarely does the literature analyse learning objectives in conjunction with the implementations of virtual laboratories. In this research, careful attention was given to ABET learning objectives while analysing virtual laboratories and bringing a prototype system into production. The incorporation of learning objectives into the design of a virtual laboratory is important and is therefore the first step in the implementation framework proposed in this research. **To the best of my knowledge, this is the first work that has explicitly analysed the potential of virtual laboratories to implement a complete list of laboratory-learning objectives.**

Prior studies have provided some informal guidelines for incorporating lecture materials into online learning systems and elements for remote labs but have not specifically addressed guidelines for the design of a virtual laboratory. In this research, through careful analysis of the literature and by incorporating the findings of student surveys and faculty and student interviews, a comprehensive list of design guidelines was developed for a virtual laboratory. Findings indicated the desire for collaboration, scheduling, and realism to support student learning objectives while being able to learn from mistakes. In this research, it was discovered that initial feedback from students was highly productive and a staged implementation with iterative feedback loops, was critical to the success of the virtual laboratory. **To the best of my knowledge, this work represents the first attempt to develop a consolidated set of general design guidelines for virtual laboratories.**

The work in this thesis was greatly assisted by feedback from the user population – the students. Students strongly expressed their desires to learn and adequately perform experiments. They expressed their needs for online communication that could help to replicate the rich interpersonal communications in the physical laboratory. Although user participation in any design process is now relatively commonplace, few of the previous reports about virtual laboratories have emphasised the usefulness of user participation in the design process. **Another contribution of this work is to reiterate the benefits that are achieved by involving the users of a virtual laboratory in the design process from the beginning.**

Many of the studies in the literature presented virtual laboratories as a replacement option, and presented findings related to how virtual laboratories meet or exceed the capabilities of physical laboratories. Other studies presented virtual laboratories as an alternative for additional access but did not provide any understanding of what considerations are important to the students receiving the additional access. In this research, both the virtual laboratory and the physical laboratory strengths and weaknesses are presented from the findings in the literature and from the student and faculty survey results. Students identified that the virtual laboratory was invaluable for test preparation and time flexibility. They also identified the need for virtual laboratories to support up-to-date designs in the real-world, where technology is being used more and students need to learn how to use the newer technologies in addition to traditional physical methods. Newer technologies are being utilized for hazardous situations, and students need access to those technologies as well. **Another contribution of this work is the conclusion that the development of virtual laboratories may considerably benefit from an initial deployment of such software tools as a complement to physical laboratories, rather than as a complete replacement.**

8.3 Limitations

The research presented in this dissertation involved the development of a Breadboard Simulator for implementation the university setting. The surveys and interviews are specific to the participants and users of the laboratory, so the findings must be understood as such. The survey responses in this research are specific to the views of students and faculty in these specific settings, and the viewpoints of students and faculty in other universities and programs may be different, however none of the findings were inconsistent with findings in prior studies.

To overcome this limitation, the approach has been to gain insights from different sources – personal insights from the author as the tool developer, from the users of the tool, and from faculty who might include such a tool in their courses. Additionally, all the specific feedback for this tool has been considered in the broader context of many reports of other deployments in the literature. Finally, these insights have been combined to give a general set of design guidelines that can be considered in many different scenarios.

The Breadboard Simulator developed for this project is specific to one area of study in the electrical engineering field. In different areas, such as anatomy or chemistry, the learning objectives may be quite different, and the resulting tools would emphasise different learning objectives. However, many of the same guidelines will apply – there is still a need to explicitly consider learning objectives, still a need to replicate the interpersonal communications of the physical lab, and still a benefit to including the users of the laboratory in the design process.

8.4 Future Research

As technology improves, so do the capabilities of LMSs and virtual laboratories. More realism in the virtual laboratories and integration of virtual laboratories with the learning curriculum, virtual reality and augmented reality are emerging areas. From the literature reviewed in this research, one challenge for virtual laboratories involves the development of the curriculum by the faculty for online instruction. More research and prototyping of efficient ways to create and maintain online instruction is needed.

The engineering cohort at University of Queensland is approximately 75% male. Research to-date has not focused on gender differences and preferences in the use of virtual laboratories. It may be that female students in electrical engineering view the laboratories more or less favourably than their male counterparts. A more controlled study of separating users into a physical laboratory only group versus a physical and simulation laboratory group might provide additional insight into differences and uses for the virtual laboratories and physical laboratories.

For the virtual laboratory tool used in this research, students used a Breadboard simulator. There is considerable additional work that could be done to improve the power and functionality of the Breadboard Simulator. One possible enhancement would be to give students the opportunity to switch usage to a schematic view or schematic design, allowing switching between the Breadboard and the schematic view. This alternate design is possible as they both used Netlist and can be simulated with the Spice package. Using this type of interface in an alternate design would enable students to experiment with their design on both interfaces.

The necessity of realism in the virtual laboratories was a recurring theme in both the literature and the student responses. One student mention that a “3D rotative view of each component and the system” would be helpful. The measurement of realism in the virtual laboratory and how it is measured would be a useful area of research. Perception-based measurements may be useful, supplemented by quantitative techniques for calculating the deviation of a virtual environment from a physical environment. As commercialization of the tools increases, a standardized measure of realism could be developed.

In addition, the development of software to simulate physical laboratories takes special skills with a variety of software tools. Research and development of standards for these tools so that components can be easily maintained and interchanged is important. Standards for integrating virtual laboratories with LMSs is important. Understanding the impact of newer technologies such as virtual reality and augmented reality, and how they may bring more realism to the virtual laboratory needs to be studied. What may be the impacts of Software as a Service (SaaS), the cloud and more vendors entering the market on implementations in virtual laboratories?

While many studies identified virtual laboratories as more cost effective, an actual cost-benefit analysis or cost-estimation process was not found. Are virtual laboratories truly less expensive and what are the key cost drivers? Research is needed to account for all the costs involved in the design, development, deployment, maintenance and support of virtual laboratories to paint a realistic picture of whether virtual laboratories are truly more cost effective.

As technology improves, the replacement and supplementation of physical laboratories with virtual laboratories is increasing. Is there a limit to the amount of replacement that can occur? As found in this research, there are different considerations depending on the academic area, so it might be useful to analyse different academic areas to develop expectations as to what those theoretical limits may be.

9 References

[1] C. Jara, F. Candelas, S. Puente and F. Torres, "Hands-on experiences of undergraduate students in automatics and robotics using a virtual and remote laboratory," *Computers and Education, 57,* pp. 2451-2461, 2011.

[2] R. Kurzweil, The law of accelerating returns. In Alan Turing: Life and Legacy of a Great Thinker (pp. 381-416), Springer Berlin Heidelberg, 2004.

[3] A. Collins and R. Halverson, Rethinking education in the age of technology: The digital revolution and schooling in America, New York: Teachers College Press, 2009.

[4] R. Goodfellow and M. Lea, Literacy in the digital university: Critical perspectives on learning, scholarship and technology, Routledge: New York and London, 2013.

[5] G. Siemens, D. Gašević and S. Dawson, "Preparing for the digital university: A review of the history and current state of distance, blended, and online learning," 2015. [Online]. Available: http://linkresearchlab.org/PreparingDigitalUniversity.pdf. [Accessed June 2017].

[6] S. Kong, T. Chan, P. Griffin, U. Hoppe, R. Huang, L. Kinshuk, C. Looi, M. Milrad, C. Norris, M. Nussbaum and M. Sharples, "E-learning in School Education in the Coming 10 Years for Developing 21st Century Skills: Critical Research," *Educational Technology & Society, 17(1),* pp. 70-78, 2014.

[7] N. Selwyn, Education and technology: Key issues and debates, New York: Continuum International Publishing Group, 2011.

[8] C. Bennett, "Online Education for More Than One Million Students," June 2016. [Online]. Available: https://www.uq.edu.au/news/article/2016/07/online-education-more-one-million-students. [Accessed August 2017].

[9] J. Marcus, "Academic Crowdsourcing Allows Lecturers to Share Ideas," January 2016. [Online]. Available: https://www.timeshighereducation.com/news/academic-crowdsourcing-allows-lecturers-share-ideas. [Accessed May 2016].

[10] "Andressen Horowitz Portfolio," 2016. [Online]. Available: http://a16z.com/portfolio/. [Accessed September 2017].

[11] T. Bliss, J. Hilton III, D. Wiley and K. Thanos, "The cost and quality of online open textbooks: Perceptions of community college faculty and students," *First Monday, 18(1),* 2013.

[12] C. Gomez, "Career-oriented education in high demand, but challenges remain," April 2014. [Online]. Available: https://www.thinkbrg.com/media/news/428_Sedehi_RRAL_April2014.pdf. [Accessed May 2016].

[13] F. Esquembre, "Facilitating the creation of virtual and remote laboratories for science and engineering education.," *IFAC-PapersOnLine, 48-29,* pp. 49-58, 2015.

[14] H. Keller and E. Keller, "Making real virtual laboratories," *The Science Education Review, CA, USA, 4(1),* pp. 2-11, 2005.

[15] S. Hubackova, "History and Perspectives of E-learning," *Procedia – Social and Behavioral Sciences, 191,* p. 1187 – 1190, 2015.

[16] I. Dobre, "Learning management systems for higher education – An overview of available options for higher education organizations," *Procedia – Social and Behavioral Sciences, 180,* pp. 313-320, 2015.

[17] M. Waheed, K. Kaurt and S. Kumar., "What role does knowledge quality play in online students' satisfaction, learning and loyalty? An empirical investigation in an e-learning context," *Journal of Computer Assisted Learning, 32,* pp. 561-575, 2016.

[18] J. Brinson, "Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A Review of the Empirical Research," *Computers and Education, 87,* pp. 218-237, 2015.

[19] A. Popovici and C. Mironov, "Students' perception on using e-learning technologies," *Procedia – Social and Behavioral Sciences, 180,* pp. 1514-1519, 2015.

[20] D. Draskovic, M. Misic and Z. Stanisavljevic, "Transition from traditional to LMS supported examining: A case study in computer engineering," *Computer Applications in Engineering Education, 24(5),* pp. 775-786, 2016.

[21] [Online]. Available: https://stackoverflow.com/. [Accessed September 2018].

[22] [Online]. Available: https://www.ratemyteachers.com/. [Accessed September 2018].

[23] S. Ros, R. Hernandez, A. Caminero, A. Robles, I. Barbero, A. Macia and P. Holgado, "On the use of extended TAM to assess students' acceptance and intent to use third-generation learning management systems," *British Journal of Educational Technology, 46(6),* pp. 1250-1271, 2014.

[24] M. Berenguel, F. Rodriguez, J. Moreno, J. Guzman and R. Gonzalez, "Tools and methodologies for teaching robotics in computer science and engineering studies.," *Computer Applications in*

Engineering Education, 24(2), pp. 202-214, 2015.

[25] H. An, S. S. Kim and B. Kim, “Teacher perspectives on online collaborative learning: Factors perceived as facilitating and impeding successful online group work.,” *Contemporary Issues in Technology and Teacher Education, 8(1),* pp. 65-83, 2008.

[26] S. Bermejo, “Cooperative electronic learning in virtual laboratories through forums,” *IEEE Transactions on Education, 48 (1),* pp. 140-149, 2005.

[27] J. Garfield, “Cooperative Learning Revisited: From an Instructional Method to a Way of Life,” *Journal of Statistics Education, 21(2),* 2013.

[28] D. I. Lewis, *The pedagogical benefits and pitfalls of virtual tools for teaching and learning laboratory practices in the Biological Sciences,* The University of Leeds: The Higher Education Academy, 2014.

[29] E. Lindsay and M. Good, “The impact of audiovisual feedback on the learning outcomes of a remote and virtual laboratory class,” *IEEE Transactions on Education,* vol. 52, no. 4, pp. 491-502, 2009.

[30] J. Mayes and C. Fowler, “Learning technology and usability: a framework for understanding courseware.,” *Interaction with Computers,* vol. 11, pp. 485-497, 1999.

[31] A. Hofstein and V. Lunetta, “The laboratory in science education: Foundations for the twenty-first century,” *Science Education, 88(1),* pp. 28-54, 2004.

[32] C. Hart, P. Mulhall, A. Berry, J. Loughran and R. Gunstone, “What is the Purpose of this Experiment? Or Can Students Learn Something from Doing Experiments,” *Journal of Research in Science Teaching, 37(7),* p. 655, 2000.

[33] J. Michael, “Where's the evidence that active learning works?,” *American Physiological Society, 30(4),* pp. 159-167, 2006.

[34] I. Gustavsson, “User-defined electrical experiments in a remote laboratory,” *American Society for Engineering Education Annual Conference & Exposition: Sesson 2359,* 2003.

[35] B. Balamuralithara and P. Woods, “An investigation on adoption of the engineering simulation lab exercise: A case study in multimedia university,” *Computer Applications in Engineering Education,* vol. 20, pp. 339-345, 2012.

[36] Y. H. Elawady and A. Tolba, “Educational objectives of different laboratory types: A comparative study,” *International Journal of Computer Science and Information Security,6(2),*

pp. 89-96, 2009.

[37] I. Abrahams and M. R., “Does practical work really work? A study of the effectiveness of practical work as a teaching and learning method in school science.,” *International Journal of Science Education,* pp. 1945-1969, 2008.

[38] M. Fiedler and E. Haruvy, “The lab versus the virtual lab and virtual field—An experimental investigation of trust games with communication,” *Journal of Economic Behavior & Organization, 72(2),* pp. 716-724, 2009.

[39] L. Feisel and A. Rosa, “The role of the laboratory in undergraduate engineering education,” *Journal of Engineering Education: 10.,* 2005.

[40] J. Sánchez, F. Esquembre, C. Martín, S. Dormido, S. Dormido-Canto, R. Canto, R. Pastor and A. Urquia, “Easy java simulations: an open-source tool to develop interactive virtual laboratories using matlab/simulink.,” 2005.

[41] C. L. Dym, A. Agogino, O. Eris, D. Frey and L. Leifer, “Engineering design thinking, teaching, and learning,” *Journal of Engineering Education, 94(1),* pp. 103-120, 2005.

[42] A. A. Gokhale, “Collaborative learning enhances critical thinking,” *Journal of Technology Education, 7(1),* p. 6, 1995.

[43] A. K. Rajput, “Simulation based loop and nodal analysis of D.C networks in LabVIEW,” *International Journal of Advanced Scientific and Technical Research, 4(3),* p. 9, 2013.

[44] J. Andújar, A. Mejías and M. Márquez, “Augmented reality for the improvement of remote laboratories: An augmented remote laboratory,” *IEEE Transactions on Education, 54(3),* 2011.

[45] R. Heradio, L. de la Torre, D. Galan, F. Cabrerizo, E. Herrera-Viedma and S. Dormido, “Virtual and remote labs in education: A bibliometric analysis,” *Computers and Education, 98,* pp. 14-38, 2016.

[46] C. Jara, F. Candelas, F. Torres, S. Dormido and F. Esquembre, “Synchronous collaboration of virtual and remote laboratories,” *Computer Applications in Engineering Education, 20(1),* pp. 124-136, 2012.

[47] L. Kriflik and J. Mullan, “Strategies to improve student reaction to group work,” *Journal of University Teaching & Learning Practice, 4(1),* p. 3, 2007.

[48] D. Johnson, R. Johnson and K. Smith, “Cooperative learning: Increasing college faculty instructional productivity,” The George Washington University, School of Education and Human

Development, Washington, D.C., 1991.

[49] AWE, “Cooperative Learning, Assessing Women in Engineering (AWE Project),” 17 August 2014. [Online]. Available: <http://www.aweonline.org>.. [Accessed February 2017].

[50] M. Prince, “Does active learning work? A review of the research,” *Journal of Engineering Education, 93(3),* pp. 223-231, 2004.

[51] J. Wang, X. Hu and J. Xi, “Cooperative learning with role play in Chinese pharmacology education,” *Indian Journal of Pharmacology, 44,* pp. 253-256, 2012.

[52] P. Häkkinen, “What makes learning and understanding in virtual teams so difficult?,” *CyberPsychology & Behavior, 7(2),* pp. 201-206, 2004.

[53] N. Capdeferro and M. Romero, “Are online learners frustrated with collaborative learning experiences?,” *The International Review of Research in Open and Distance Learning, 13(2),* pp. 26-44, 2012.

[54] M. H. Koh and J. Hill, “Student perceptions of groupwork in an online course: Benefits and challenges,” *International Journal of E-Learning & Distance Education, 23(2),* pp. 69-92, 2009.

[55] M. E. Warkentin, L. Sayeed and R. Hightower, “Virtual teams versus face□to□face teams: An exploratory study of a web□based conference system,” *Decision Sciences, 28(4),* pp. 975-996, 1997.

[56] J. Garfield, “Teaching statistics using small-group cooperative learning,” *Journal of Statistics Education, 1(1),* pp. 1-9, 1993.

[57] T. S. Roberts and J. McInnerney, “Seven problems of online group learning (and their solutions),” *Educational Technology & Society, 10(4),* pp. 257-268, 2007.

[58] R. Tiwari and K. Singh, “Virtualisation of engineering discipline experiments for an Internet-based remote laboratory,” *Australasian Journal of Educational Technology, 27(4),* pp. 671 - 692, 2011.

[59] A. Alkouz, A. Al-Zoubi and M. Otair, “J2ME-based mobile virtual laboratory for engineering education,” *International Journal of Interactive Mobile Technologies (iJIM),* vol. 2, no. 2, 2008.

[60] J. V. Nickerson, J. Corter, S. Esche and C. Chassapis, “A model for evaluating the effectiveness of remote engineering laboratories and simulations in education,” *Computers & Education, 49(3),* pp. 708-725, 2007.

[61] H. Babateen, “The role of virtual laboratories in science education.,” in *International Proceedings of Computer Science and Information Technology, 12*, 2011.

[62] J. Ma and J. Nickerson, “Hands-on, simulated, and remote laboratories: A comparative literature review,” *ACM Computing Surveys (CSUR), 38(3),* p. 7, 2006.

[63] M. Schulz, F. Chen and L. Payne, “Real-time animation of equipment in a remote laboratory,” *2014 11th International Conference on Remote Engineering and Virtual Instrumentation (REV),* pp. 172-176, 2014.

[64] L. Freina and M. Ott, “A literature review on immersive virtual reality in education: State of the art and perspectives,” *eLearning & Software for Education,* vol. 1, 2015.

[65] E. Dieterle, Encyclopedia of Multimedia Technology and Networking, Second Edition, IGI Global, 2009, pp. 1033-1041.

[66] N. Finkelstein, W. Adams, P. Kohl and N. Podolefsky, “Can computer simulations replace real equipment in undergraduate laboratories?,” University of Colorado, Boulder, 2005.

[67] L. a. P. Guelman, “The Influence of Tablet PCs on Students' Use of Multiple Representations in Lab Reports,” in *AIP Conference Proceedings*, 2009.

[68] N. Aliane, R. Pastor and G. Mariscal, “Limitations of remote laboratories in control engineering education,” *International Journal of Online Engineering (iJOE), 6(1),* pp. 31-33, 2010.

[69] P. Orduna, E. Sancristobal, M. Emaldi, M. Castro, D. López-de-Ipina and J. Garcia-Zubia, “Modelling remote laboratories integrations in e-Learning tools through remote laboratories federation protocols,” *IEEE,* 2012.

[70] M. Gardner and J. Elliot, “Immersive education laboratory: understanding affordances, structuring experiences, and creating constructivist, collaborative processes, in mixed-reality smart environments.,” *EAI Endorsed Transactions on Future Intelligent Educational Environments,* vol. 1, no. 1, 2014.

[71] F. Liarokapis, N. Mourkoussis, M. White, J. Darcy, M. Sifniotis, P. Petridis, A. Basu and P. Lister, “Web3D and augmented reality to support engineering education,” *World Transactions on Engineering and Technology Education,* vol. 3, no. 1, pp. 11-14, 2004.

[72] M. Budhu, “Virtual laboratories for engineering education,” *International Conference on Engineering Education,* vol. 1, p. 334, 2000.

[73] L. Flick and R. Bell, “Preparing tomorrow's science teachers to use technology: Guidelines for science educators,” *Contemporary Issues in Technology and Teacher Education, 1(1),* pp. 39-60,

2000.

[74] E. Harry and B. Edward, “Making real virtual lab,” *The Science Education Review,* 2005.

[75] Z. Yi, J. Jian-Jun and F. Shao-Chun, “A LabVIEW-based, interactive virtual laboratory for electronic engineering education,” *International Journal of Engineering Education, 21(1),* pp. 94-102, 2005.

[76] J. Frank and V. Kapila, “Mixed-reality learning environments: Integrating mobile interfaces with laboratory test-beds,” *Computers and Education, 110,* pp. 88-104, 2017.

[77] C. Chan and W. Fok, “Evaluating learning experiences in virtual laboratory training through student perceptions: a case study in Electrical and Electronic Engineering at the University of Hong Kong,” *Engineering Education, 4(2),* pp. 70-75, 2009.

[78] M. T. Valdez, C. Ferreira and F. Barbosa, “Software packages to support electrical engineering virtual lab,” *International Journal of Online Engineering (iJOE), 8(S2),* pp. 19-23, 2012.

[79] B. Dalgarno and M. Lee, “What are the learning affordances of 3-D virtual environments?,” *British Journal of Educational Technology,* vol. 41, no. 1, pp. 10-32, 2010.

[80] J. L. Hardison, K. DeLong, P. Bailey and V. Harward, “Deploying interactive remote laboratories using the iLab Shared Architecture,” *38th ASEE/IEEE Frontiers in Education Conference,* pp. S2A-1-S2A-6, 2008.

[81] V. Potkonjak, M. Gardner, V. Callaghan, P. Mattila, C. Guetl, V. Petrovic and K. Jovanovic, “Virtual laboratories for education in science, technology, and engineering: A review.,” *Computers & Education,* vol. April, pp. 309-327, 2016.

[82] L. Gomes and S. Bogosyan, “Current trends in remote laboratories,” *IEEE Transactions on Industrial Electronics, 56(12),* p. 4744–4756, 2009.

[83] K. Page, M. Levesley, E. Read, B. Hanson and J. Gallagher, “Data sharing (DaSh) for collaborative learning in laboratories,” *Engineering Education, 4(2),* pp. 37-51, 2009.

[84] C. Tuysuz, “The effect of the virtual laboratory on students’ achievement and attitude in chemistry,” *International Online Journal of Educational Sciences, 2(1),* pp. 37-53, 2010.

[85] T. De Jong, M. Linn and Z. Zacharia, “Physical and virtual laboratories in science and engineering education,” *Science, 340(6130),* pp. 305-308, 2013.

[86] Y. Y. H. Fung, “Collaborative online learning: Interaction patterns and limiting factors,” *Open*

Learning: The Journal of Open, Distance and e-Learning, 19(2), pp. 135-149, 2004.

[87] J. Rossiter, “Low production cost virtual modelling and control laboratories for chemical engineering students,” *IFAC-PapersOnLine, 49(6),* pp. 230-235, 2016.

[88] M. Stefanovic, “The objectives, architectures and effects of distance learning laboratories for industrial engineering education,” *Computers and Education, 69,* pp. 250-262, 2013.

[89] B. Balakrishnan, Laboratories in Engineering: A Comparative Study, LAMBERT Academic Publishing, 2013.

[90] N. Cagiltay, E. Aydin, C. Aydin, A. Kara and M. Alexandru, “Seven principles of instructional content design for a remote laboratory: A case study on ERRL,” *IEEE Transactions on Education,* vol. 54, no. 2, pp. 320-327, 2011.

[91] A. Pretorius, “Factors that contribute towards improving learning effectiveness using a specific learning management system (LMS) at the Military Academy (MA): A demonstration,” *Campus-Wide Information Systems, 27(5),* pp. 318-340, 2010.

[92] J. Liang, “A web-based training framework in automotive electric education,” *Computer Applications in Engineering Education, 18,* pp. 619-633, 2009.

[93] D. Whitworth and K. Wright, “Online assessment of learning and engagement in university laboratory practicals,” *British Journal of Educational Technology,* vol. 46, no. 6, pp. 1201-1213, 2015.

[94] T. McLaughlin and Z. Yan, “Diverse delivery methods and strong psychological benefits: A review of online formative assessment,” *Journal of Computer Assisted Learning,* vol. 33, no. 6, pp. 562-574, 2017.

[95] M. Bahar and M. Asil, “Attitude towards e-assessment: Influence of gender, computer usage and level of education,” *Open Learning: The Journal of Open, Distance and E-learning,* pp. 1-17, 2018.

[96] A. Gampe, A. Melkonyan, M. Pontual and D. Akopian, “An assessment of remote laboratory experiments in radio communication,” *IEEE Transactions on Education,* vol. 57, no. 1, pp. 12-19, 2014.

[97] W. Morton and J. Uhomoibhi, “E-laboratory design and implementation for enhanced science, technology and engineering education,” *Campus-Wide Information Systems, 28(5),* pp. 367- 377, 2011.

[98] B. Mashaw, “A model for measuring effectiveness of an online course,” *Decision Sciences Journal of Innovative Education, 10(2),* pp. 189-221, 2012.

[99] T. Wolf, “Assessing student learning in a virtual laboratory environment,” *IEEE Transactions on Education, 53(2),* p. 7, 2010.

[100] C. Bright, E. Lindsay, D. Lowe, S. Murray and D. Liu, “Factors that impact learning outcomes in both simulation and remote laboratories.,” *Proceedings of the World Conference on Educational Multimedia, Hypermedia and Telecomm. (Ed-. Media '08),* p. 15, 2008.

[101] E. Australia, “Program Accreditation,” 22 September 2014. [Online]. Available: http://www.engineersaustralia.org.au/about-us/program-accreditation..

[102] D. Shin, E. Yoon, K. Lee and E. Lee, “A web-based, interactive virtual laboratory system for unit operations and process systems engineering education: issues, design and implementation,” *Computers & Chemical Engineering, 26(2),* pp. 319-330, 2002.

[103] M. Parten, “Using virtual instruments in a measurements laboratory,” 2003. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.586.1890&rep=rep1&type=pdf. [Accessed May 2016].

[104] K. P. Chien, “Learning differences and eye fixation patterns in virtual and physical science laboratories,” *Elsevier: Computers & Education,* vol. 82, pp. 191-201, 2015.

[105] P. Hatherly, S. Jordan and A. Cayless, “Interactive screen experiments innovative virtual laboratories for distance learners,” *European Journal of Physics, 30(4),* pp. 751-762, 2009.

[106] L. Urdaneta and R. Garrick, “Implementing a virtual laboratory for a directed and synchronous student learning experience; Combining virtual and real experimentation: An effort to enhance students’conceptual understanding of fluid power,” 2012. [Online]. Available: https://www.asee.org/public/conferences/8/papers/4760/download. [Accessed January 2017].

[107] M. S. Williams, “Trends in engineering education: using ABET’s program outcomes as a framework for change,” *Journal of Engineering Education: School of Information Science and Learning Technology, Columbia, MO,* 2012.

[108] J. Creswell, Research design: Qualitative, quantitative, and mixed methods approaches, New York: Sage Publications, 2013.

[109] D. Levac, H. Colquhoun and K. K. O’Brien, “Scoping studies: Advancing the Methodology,” *Implementation Science, 5,* pp. 1-9, 2010.

[110] H. Hsieh and S. Shannon, “Three approaches to qualitative content analysis,” *Qualitative Health Research, 15(9),* pp. 1277-1288, 2005.

[111] D. Thiel, Research Methods for Engineers, Cambridge: Cambridge University Press, 2014.

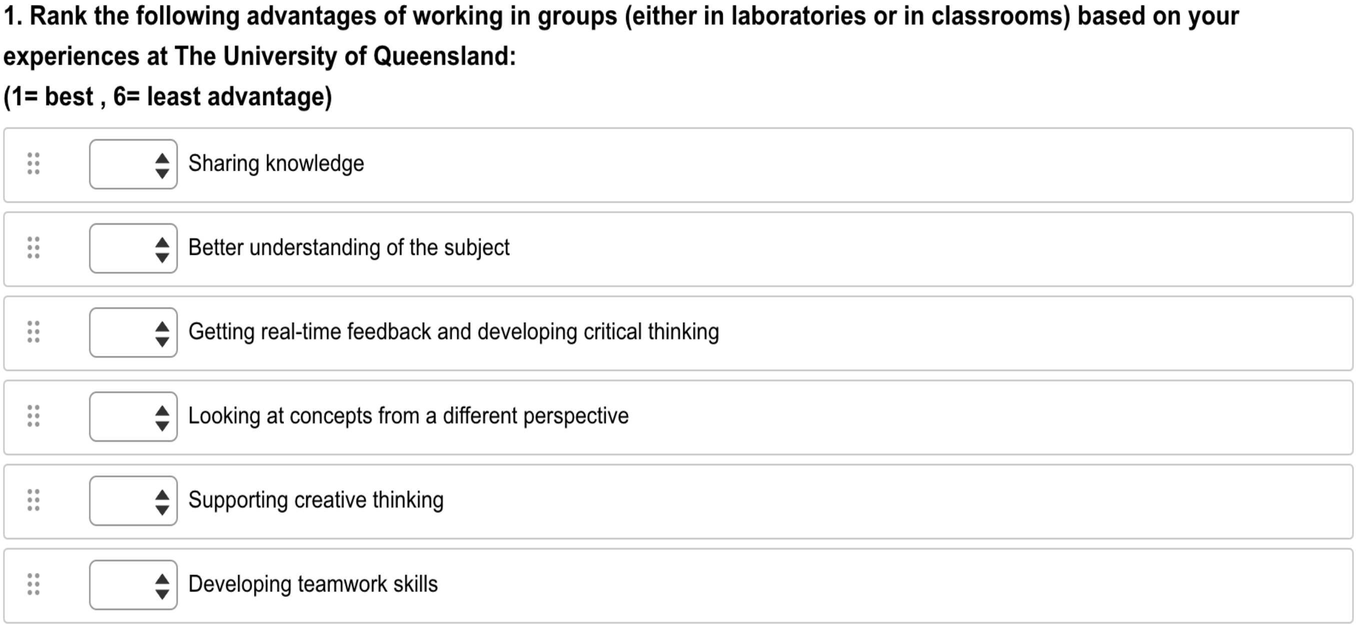
[112] P. Biemer, “Total survey error: Design, implementation and evaluation,” *Public Opinion Quarterly,* vol. 74, no. 5, pp. 817-848, 2010.

[113] H. Boone and D. Boone, “Analyzing Likert data,” *Journal of Extension,* vol. 50, no. 2, 2012.

[114] R. Fruchter, “Dimensions of teamwork education,” *International Journal of Engineering Education, 17(4/5),* pp. 426-430, 2001.

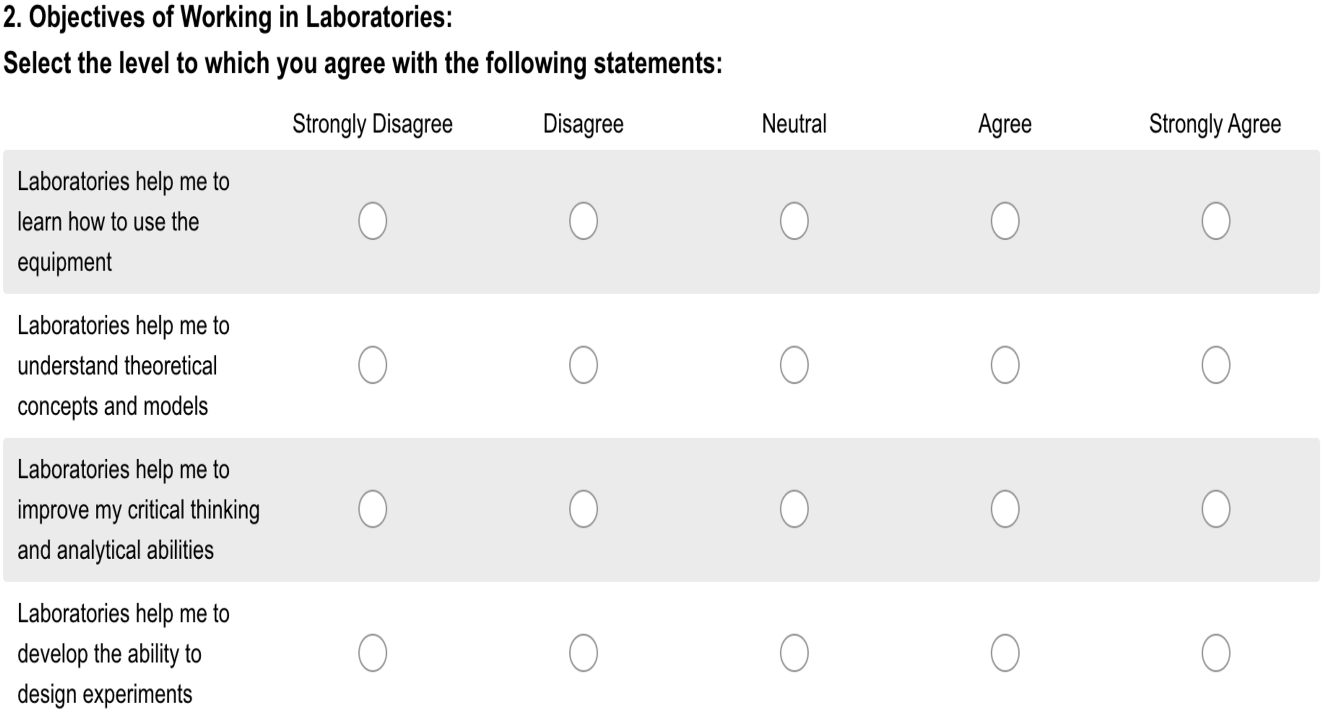
[115] “Maker Spaces,” Digital Technologies Hub, [Online]. Available: https://www.digitaltechnologieshub.edu.au/teachers/topics/maker-spaces. [Accessed 19 September 2018].

Appendix I - First Survey Questions (Pre-Implementation Survey)



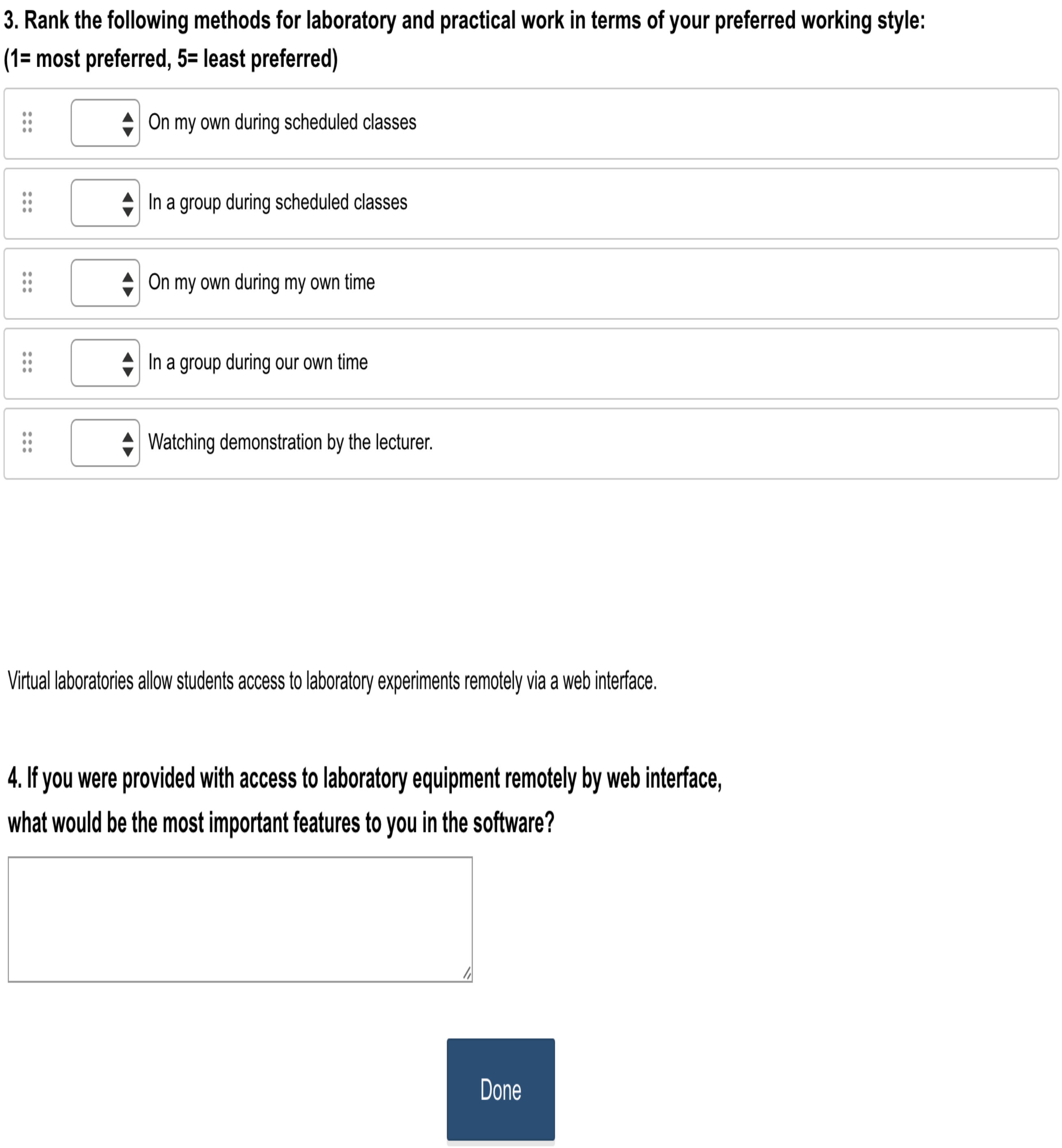
1. Rank the following advantages of working in groups (either in laboratories or in classrooms) based on your experiences at The University of Queensland:
(1= best , 6= least advantage)

- Sharing knowledge
- Better understanding of the subject
- Getting real-time feedback and developing critical thinking
- Looking at concepts from a different perspective
- Supporting creative thinking
- Developing teamwork skills



2. Objectives of Working in Laboratories:
Select the level to which you agree with the following statements:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Laboratories help me to learn how to use the equipment	○	○	○	○	○
Laboratories help me to understand theoretical concepts and models	○	○	○	○	○
Laboratories help me to improve my critical thinking and analytical abilities	○	○	○	○	○
Laboratories help me to develop the ability to design experiments	○	○	○	○	○



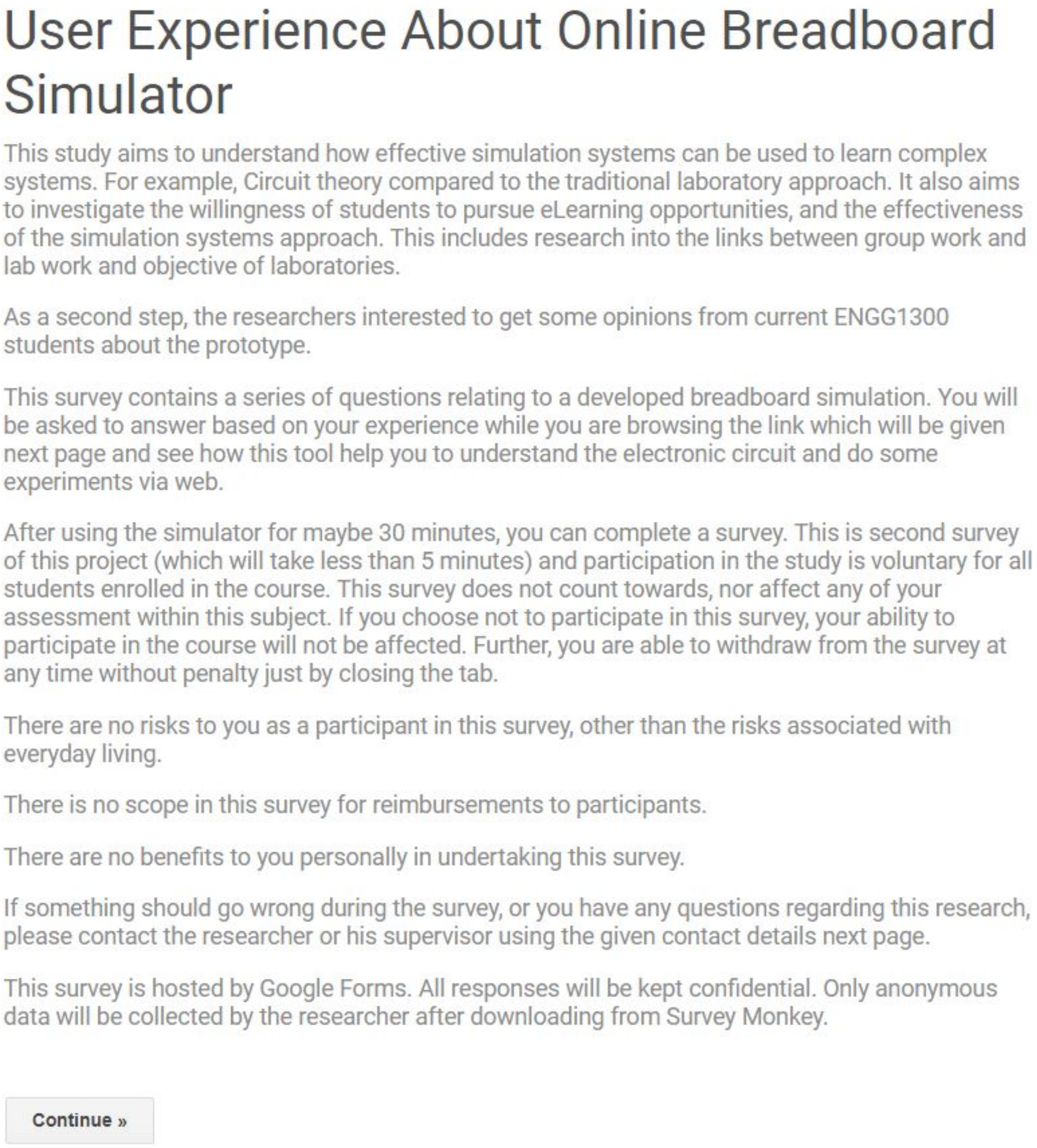
3. Rank the following methods for laboratory and practical work in terms of your preferred working style:
(1= most preferred, 5= least preferred)

- On my own during scheduled classes
- In a group during scheduled classes
- On my own during my own time
- In a group during our own time
- Watching demonstration by the lecturer.

Virtual laboratories allow students access to laboratory experiments remotely via a web interface.

4. If you were provided with access to laboratory equipment remotely by web interface, what would be the most important features to you in the software?

Appendix II Second Survey Questions (Post-Trial Implementation –Part 1)



User Experience About Online Breadboard Simulator

This study aims to understand how effective simulation systems can be used to learn complex systems. For example, Circuit theory compared to the traditional laboratory approach. It also aims to investigate the willingness of students to pursue eLearning opportunities, and the effectiveness of the simulation systems approach. This includes research into the links between group work and lab work and objective of laboratories.

As a second step, the researchers interested to get some opinions from current ENGG1300 students about the prototype.

This survey contains a series of questions relating to a developed breadboard simulation. You will be asked to answer based on your experience while you are browsing the link which will be given next page and see how this tool help you to understand the electronic circuit and do some experiments via web.

After using the simulator for maybe 30 minutes, you can complete a survey. This is second survey of this project (which will take less than 5 minutes) and participation in the study is voluntary for all students enrolled in the course. This survey does not count towards, nor affect any of your assessment within this subject. If you choose not to participate in this survey, your ability to participate in the course will not be affected. Further, you are able to withdraw from the survey at any time without penalty just by closing the tab.

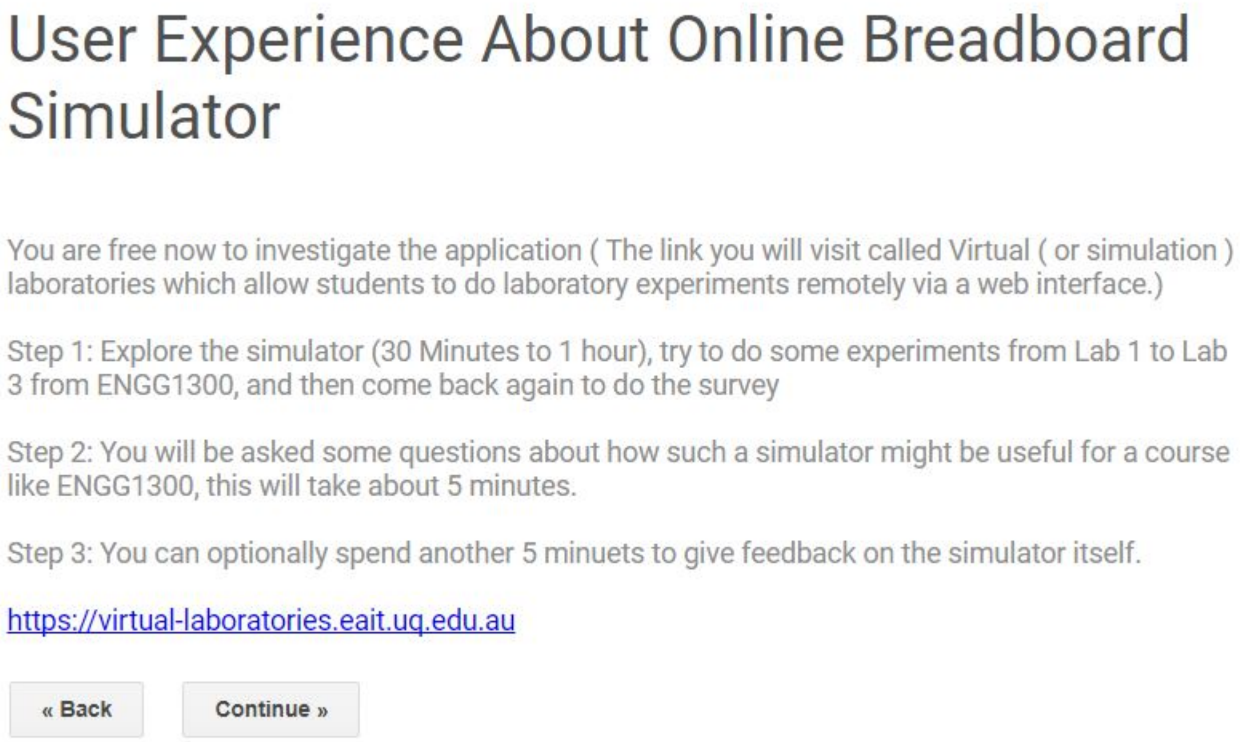
There are no risks to you as a participant in this survey, other than the risks associated with everyday living.

There is no scope in this survey for reimbursements to participants.

There are no benefits to you personally in undertaking this survey.

If something should go wrong during the survey, or you have any questions regarding this research, please contact the researcher or his supervisor using the given contact details next page.

This survey is hosted by Google Forms. All responses will be kept confidential. Only anonymous data will be collected by the researcher after downloading from Survey Monkey.



User Experience About Online Breadboard Simulator

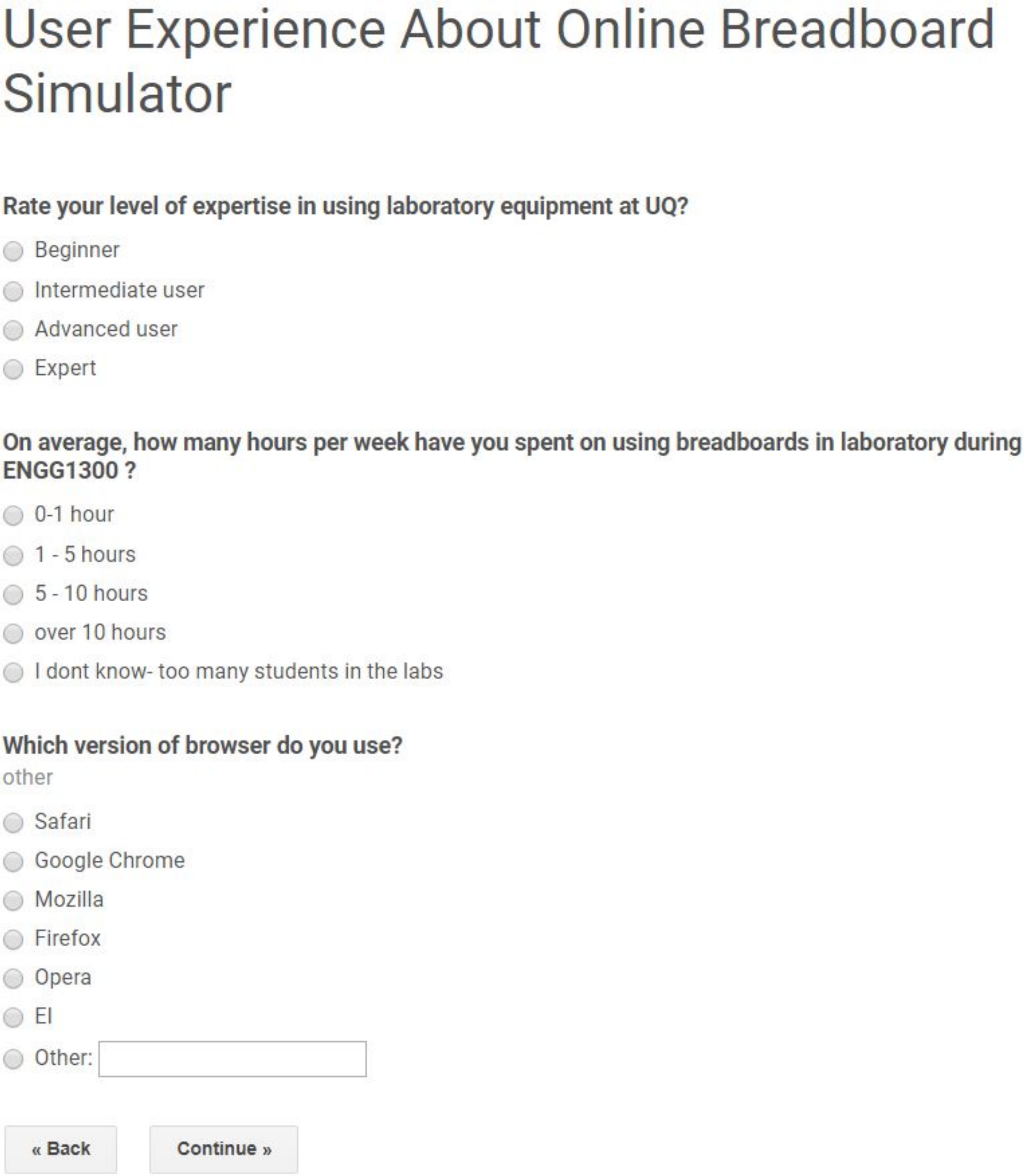
You are free now to investigate the application (The link you will visit called Virtual (or simulation) laboratories which allow students to do laboratory experiments remotely via a web interface.)

Step 1: Explore the simulator (30 Minutes to 1 hour), try to do some experiments from Lab 1 to Lab 3 from ENGG1300, and then come back again to do the survey

Step 2: You will be asked some questions about how such a simulator might be useful for a course like ENGG1300, this will take about 5 minutes.

Step 3: You can optionally spend another 5 minuets to give feedback on the simulator itself.

https://virtual-laboratories.eait.uq.edu.au



User Experience About Online Breadboard Simulator

Rate your level of expertise in using laboratory equipment at UQ?

- ○ Beginner
- ○ Intermediate user
- ○ Advanced user
- ○ Expert

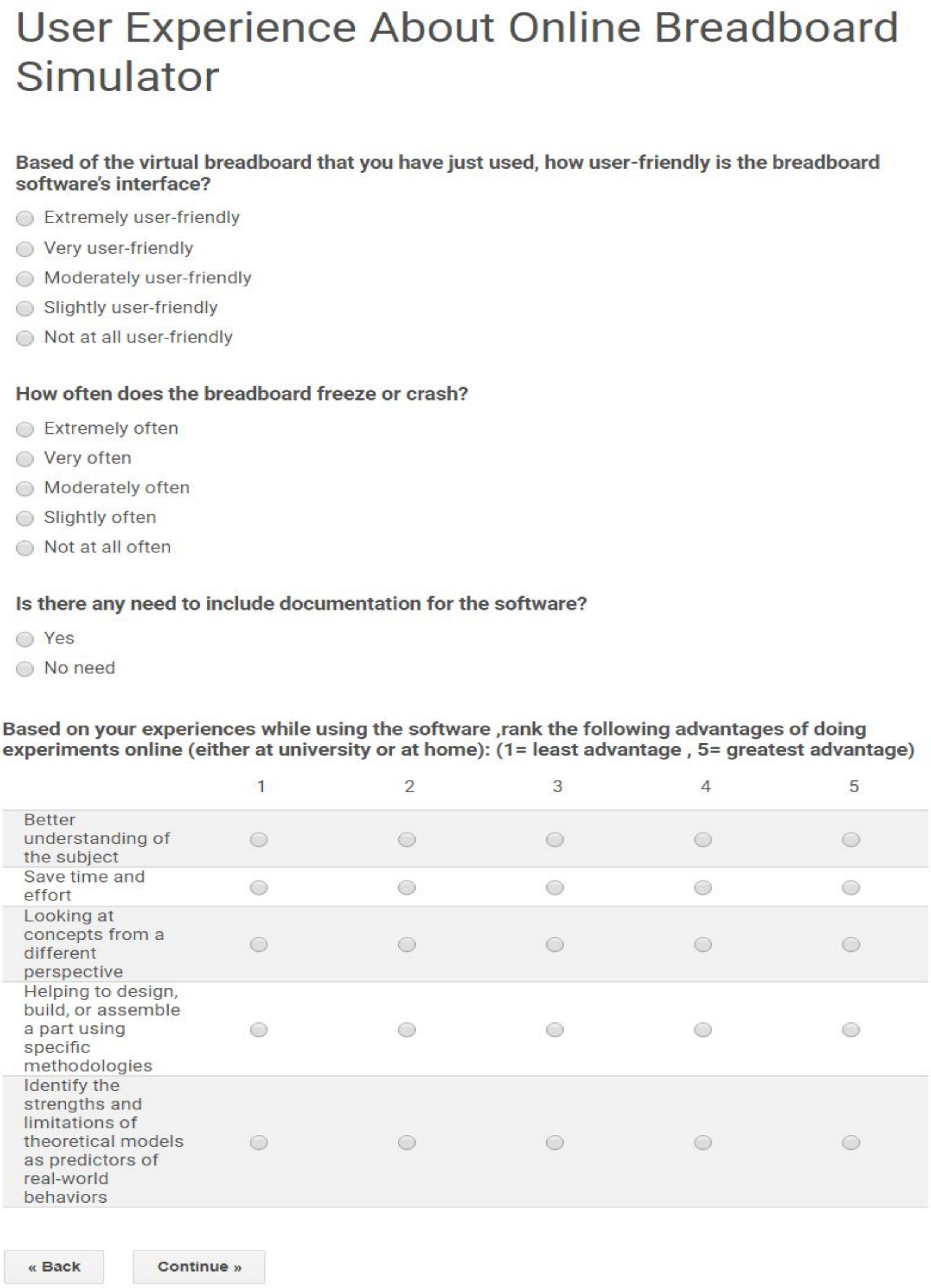
On average, how many hours per week have you spent on using breadboards in laboratory during ENGG1300 ?

- ○ 0-1 hour
- ○ 1 - 5 hours
- ○ 5 - 10 hours
- ○ over 10 hours
- ○ I dont know- too many students in the labs

Which version of browser do you use?

other

- ○ Safari
- ○ Google Chrome
- ○ Mozilla
- ○ Firefox
- ○ Opera
- ○ EI
- ○ Other: ☐



User Experience About Online Breadboard Simulator

Based of the virtual breadboard that you have just used, how user-friendly is the breadboard software's interface?

- ○ Extremely user-friendly
- ○ Very user-friendly
- ○ Moderately user-friendly
- ○ Slightly user-friendly
- ○ Not at all user-friendly

How often does the breadboard freeze or crash?

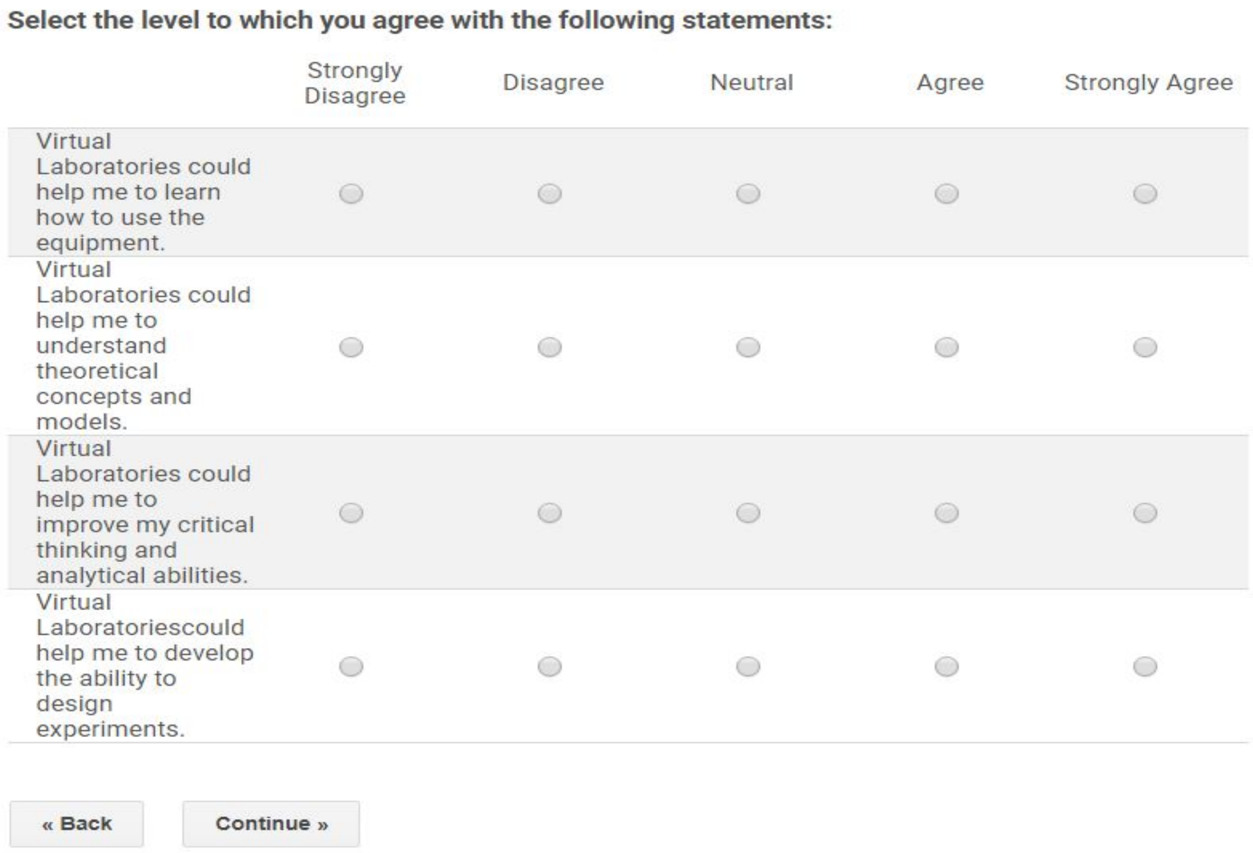
- ○ Extremely often
- ○ Very often
- ○ Moderately often
- ○ Slightly often
- ○ Not at all often

Is there any need to include documentation for the software?

- ○ Yes
- ○ No need

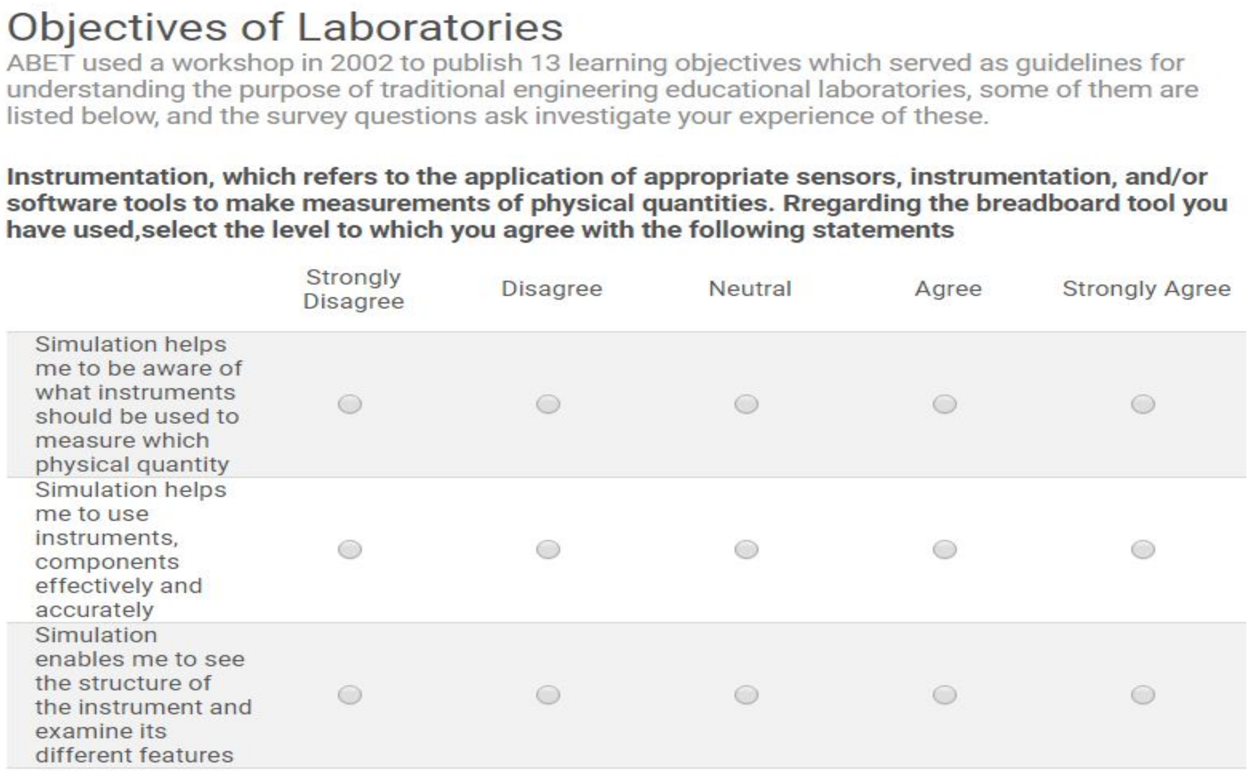
Based on your experiences while using the software ,rank the following advantages of doing experiments online (either at university or at home): (1= least advantage , 5= greatest advantage)

	1	2	3	4	5
Better understanding of the subject	○	○	○	○	○
Save time and effort	○	○	○	○	○
Looking at concepts from a different perspective	○	○	○	○	○
Helping to design, build, or assemble a part using specific methodologies	○	○	○	○	○
Identify the strengths and limitations of theoretical models as predictors of real-world behaviors	○	○	○	○	○



Select the level to which you agree with the following statements:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Virtual Laboratories could help me to learn how to use the equipment.	○	○	○	○	○
Virtual Laboratories could help me to understand theoretical concepts and models.	○	○	○	○	○
Virtual Laboratories could help me to improve my critical thinking and analytical abilities.	○	○	○	○	○
Virtual Laboratoriescould help me to develop the ability to design experiments.	○	○	○	○	○

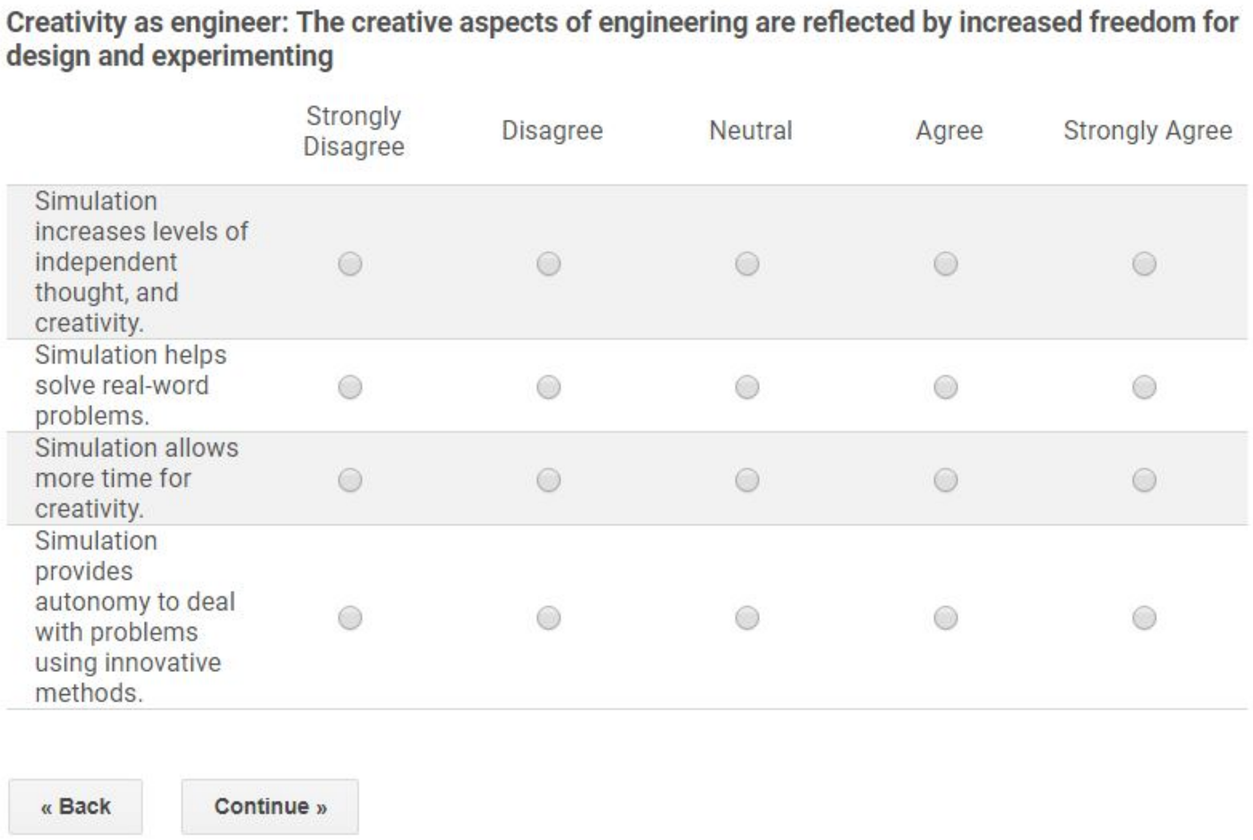


Objectives of Laboratories

ABET used a workshop in 2002 to publish 13 learning objectives which served as guidelines for understanding the purpose of traditional engineering educational laboratories, some of them are listed below, and the survey questions ask investigate your experience of these.

Instrumentation, which refers to the application of appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities. Rregarding the breadboard tool you have used,select the level to which you agree with the following statements

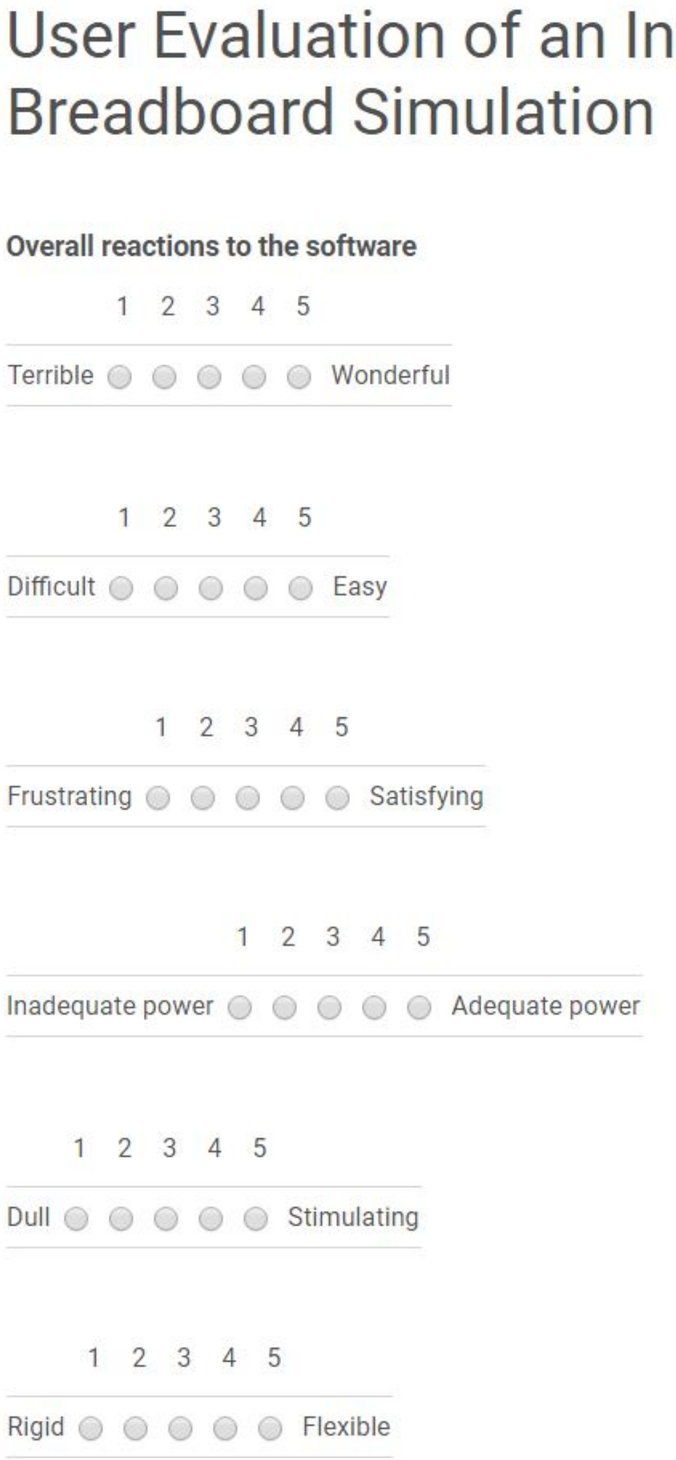
	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Simulation helps me to be aware of what instruments should be used to measure which physical quantity	○	○	○	○	○
Simulation helps me to use instruments, components effectively and accurately	○	○	○	○	○
Simulation enables me to see the structure of the instrument and examine its different features	○	○	○	○	○



Creativity as engineer: The creative aspects of engineering are reflected by increased freedom for design and experimenting

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Simulation increases levels of independent thought, and creativity.	○	○	○	○	○
Simulation helps solve real-word problems.	○	○	○	○	○
Simulation allows more time for creativity.	○	○	○	○	○
Simulation provides autonomy to deal with problems using innovative methods.	○	○	○	○	○

Appendix III Second Survey Questions (Second Part)



User Evaluation of an Interactive Breadboard Simulation

Overall reactions to the software

	1	2	3	4	5	
Terrible	○	○	○	○	○	Wonderful

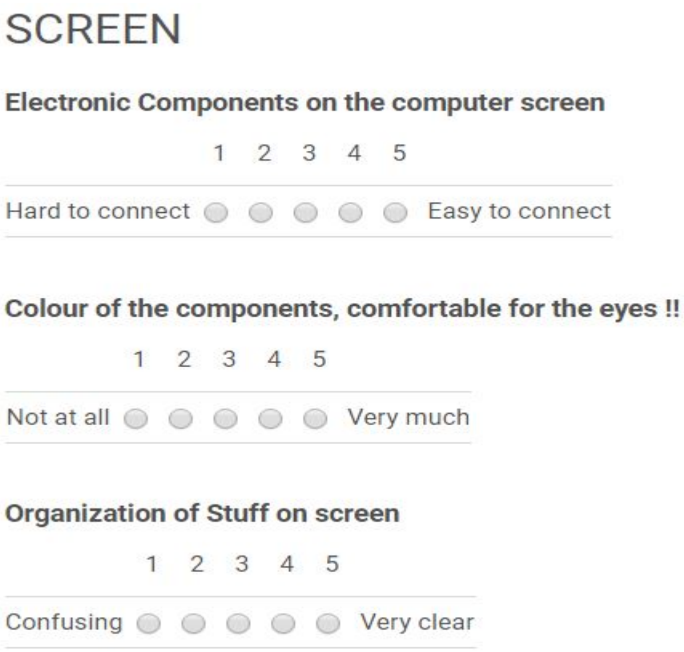
	1	2	3	4	5	
Difficult	○	○	○	○	○	Easy

	1	2	3	4	5	
Frustrating	○	○	○	○	○	Satisfying

	1	2	3	4	5	
Inadequate power	○	○	○	○	○	Adequate power

	1	2	3	4	5	
Dull	○	○	○	○	○	Stimulating

	1	2	3	4	5	
Rigid	○	○	○	○	○	Flexible



SCREEN

Electronic Components on the computer screen

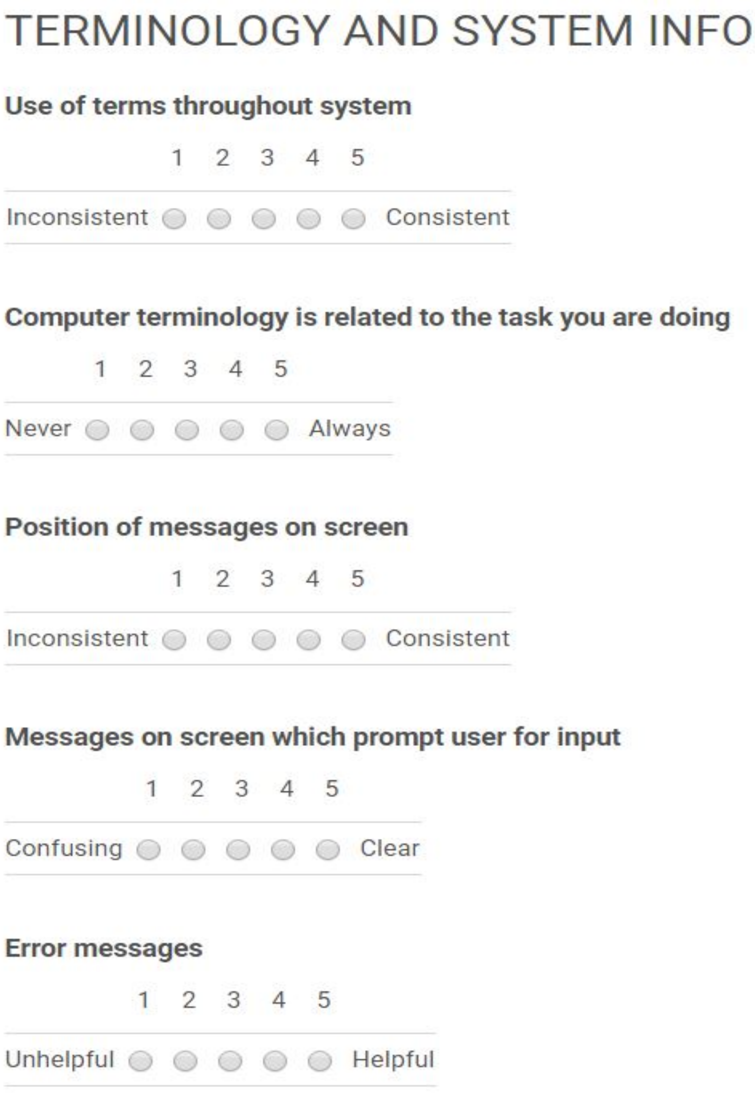
	1	2	3	4	5	
Hard to connect	○	○	○	○	○	Easy to connect

Colour of the components, comfortable for the eyes !!

	1	2	3	4	5	
Not at all	○	○	○	○	○	Very much

Organization of Stuff on screen

	1	2	3	4	5	
Confusing	○	○	○	○	○	Very clear



TERMINOLOGY AND SYSTEM INFORMATION

Use of terms throughout system

	1	2	3	4	5	
Inconsistent	○	○	○	○	○	Consistent

Computer terminology is related to the task you are doing

	1	2	3	4	5	
Never	○	○	○	○	○	Always

Position of messages on screen

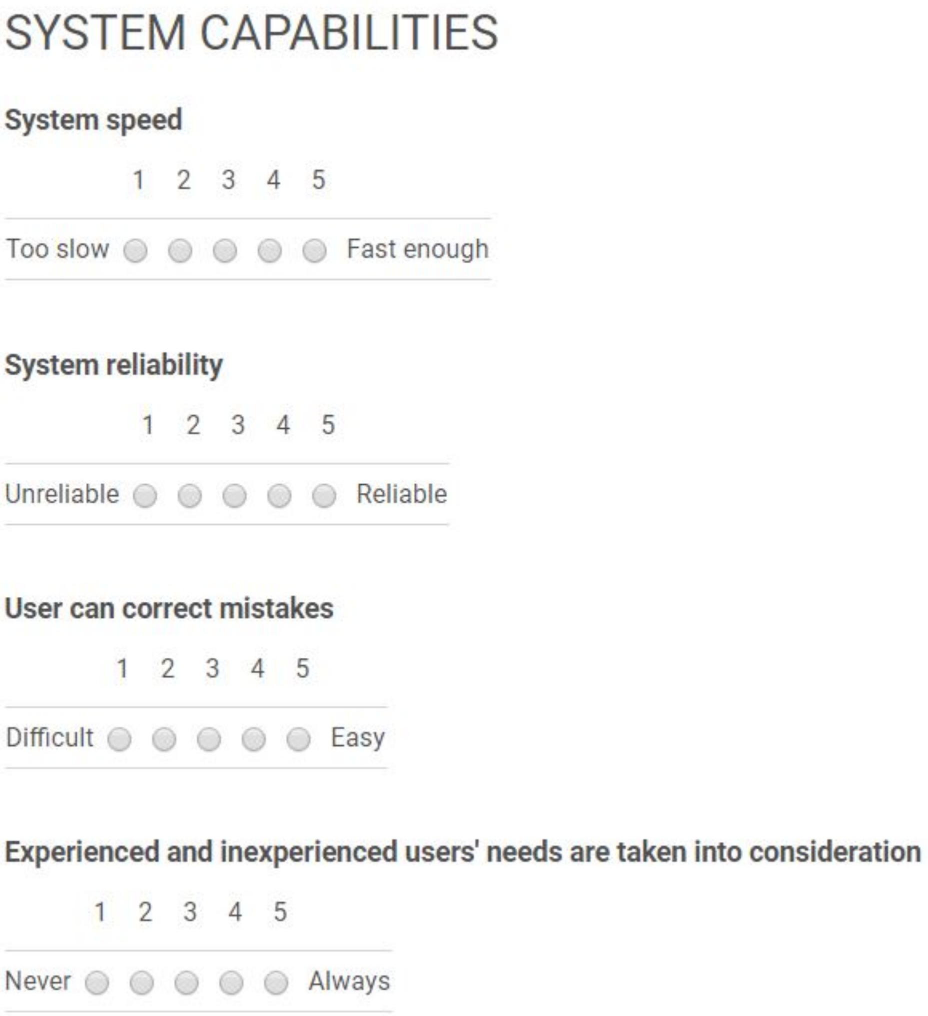
	1	2	3	4	5	
Inconsistent	○	○	○	○	○	Consistent

Messages on screen which prompt user for input

	1	2	3	4	5	
Confusing	○	○	○	○	○	Clear

Error messages

	1	2	3	4	5	
Unhelpful	○	○	○	○	○	Helpful



SYSTEM CAPABILITIES

System speed

	1	2	3	4	5	
Too slow	○	○	○	○	○	Fast enough

System reliability

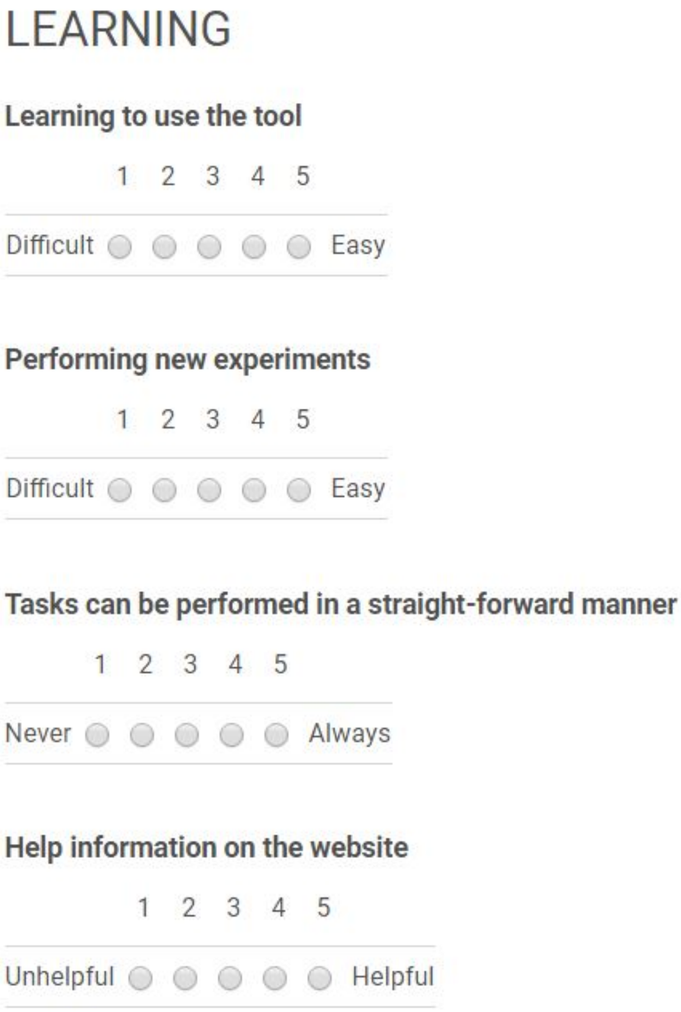
	1	2	3	4	5	
Unreliable	○	○	○	○	○	Reliable

User can correct mistakes

	1	2	3	4	5	
Difficult	○	○	○	○	○	Easy

Experienced and inexperienced users' needs are taken into consideration

	1	2	3	4	5	
Never	○	○	○	○	○	Always



LEARNING

Learning to use the tool

	1	2	3	4	5	
Difficult	○	○	○	○	○	Easy

Performing new experiments

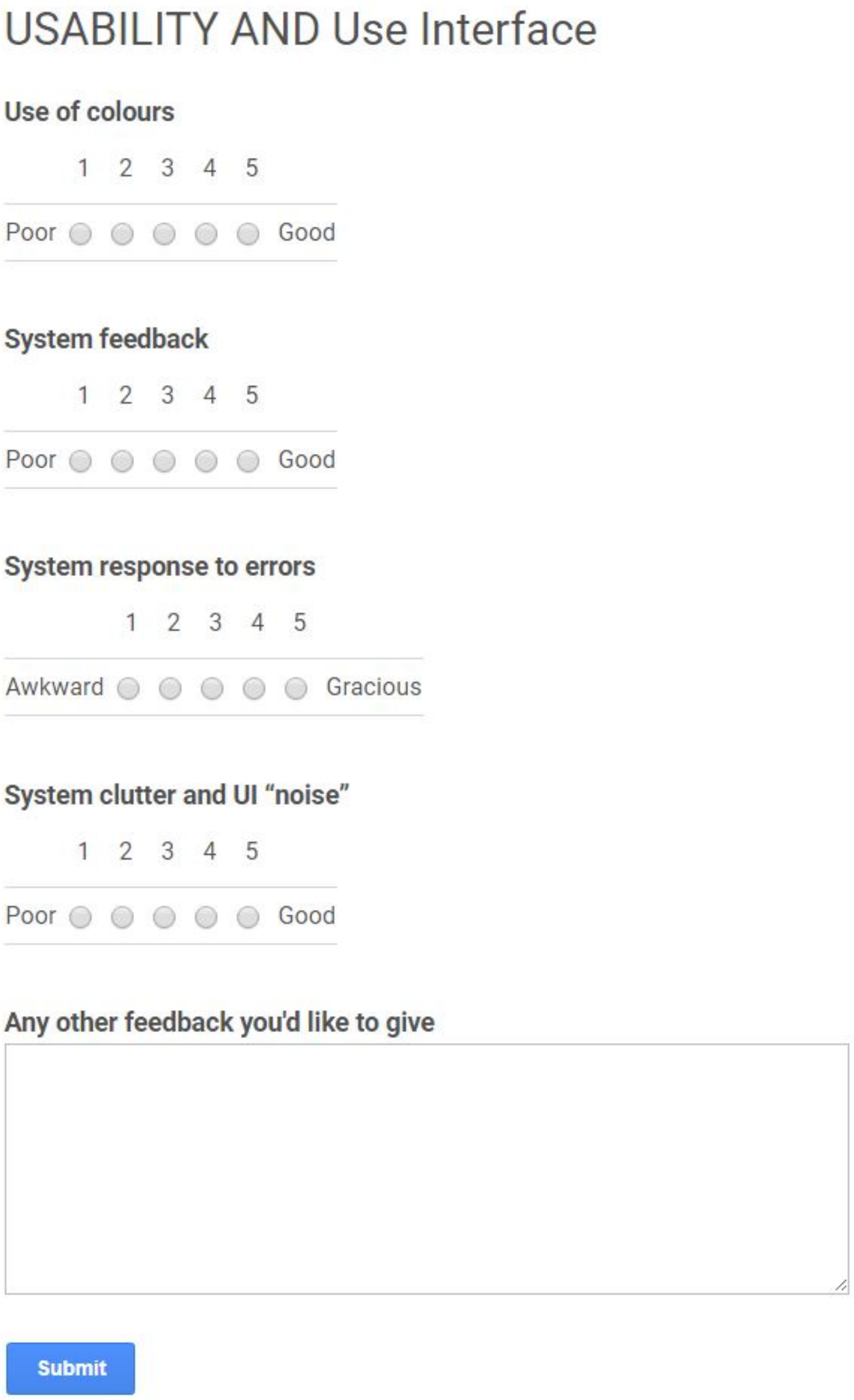
	1	2	3	4	5	
Difficult	○	○	○	○	○	Easy

Tasks can be performed in a straight-forward manner

	1	2	3	4	5	
Never	○	○	○	○	○	Always

Help information on the website

	1	2	3	4	5	
Unhelpful	○	○	○	○	○	Helpful



USABILITY AND Use Interface

Use of colours

	1	2	3	4	5	
Poor	○	○	○	○	○	Good

System feedback

	1	2	3	4	5	
Poor	○	○	○	○	○	Good

System response to errors

	1	2	3	4	5	
Awkward	○	○	○	○	○	Gracious

System clutter and UI “noise”

	1	2	3	4	5	
Poor	○	○	○	○	○	Good

Any other feedback you'd like to give

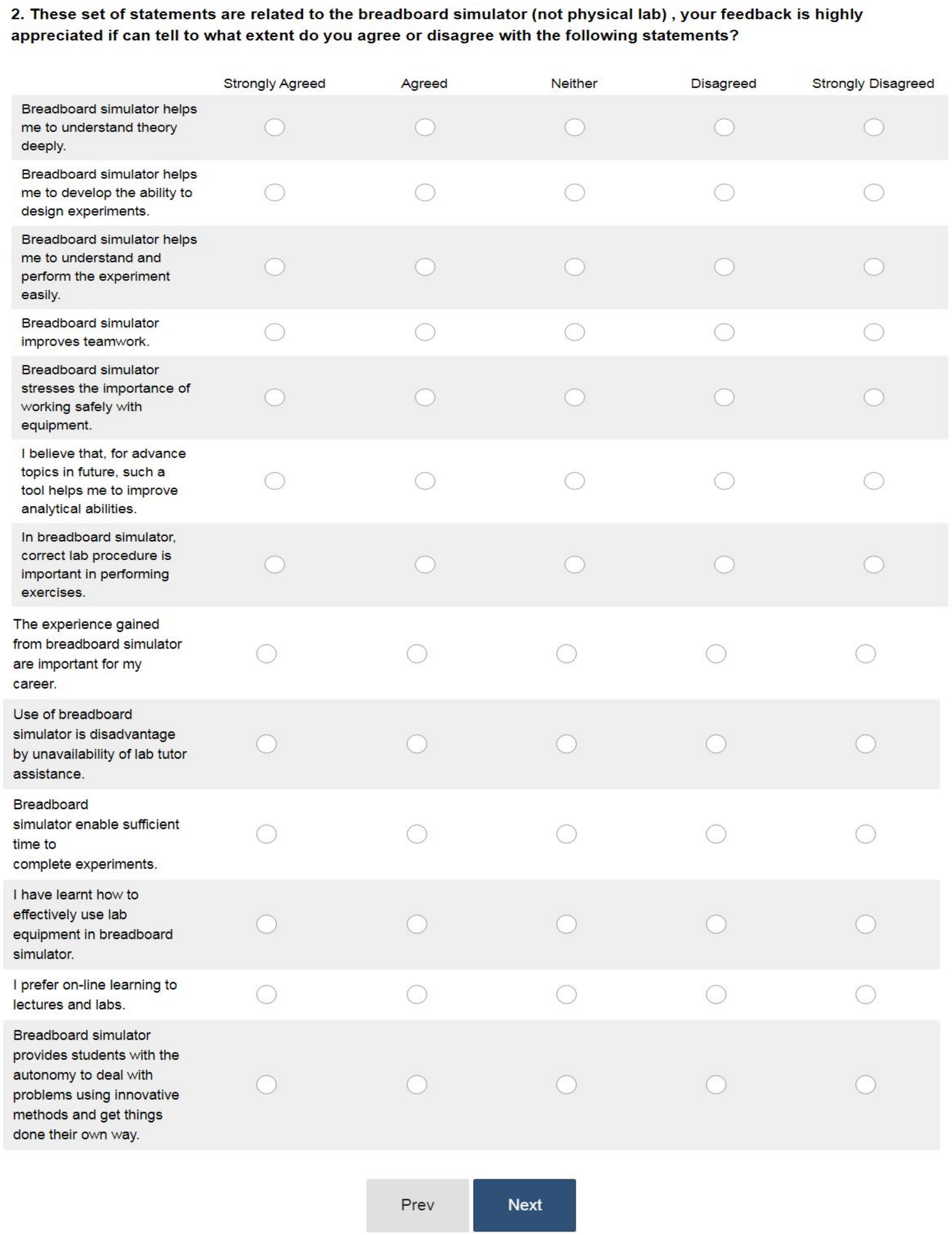
Appendix IV- Post-Production Implementation Survey

User experience about UQ's labs and online Breadboard simulator

1. These statements are about your experience in undertaking ENGG1200 labs,To what extent do you agree or disagree with the following statements?

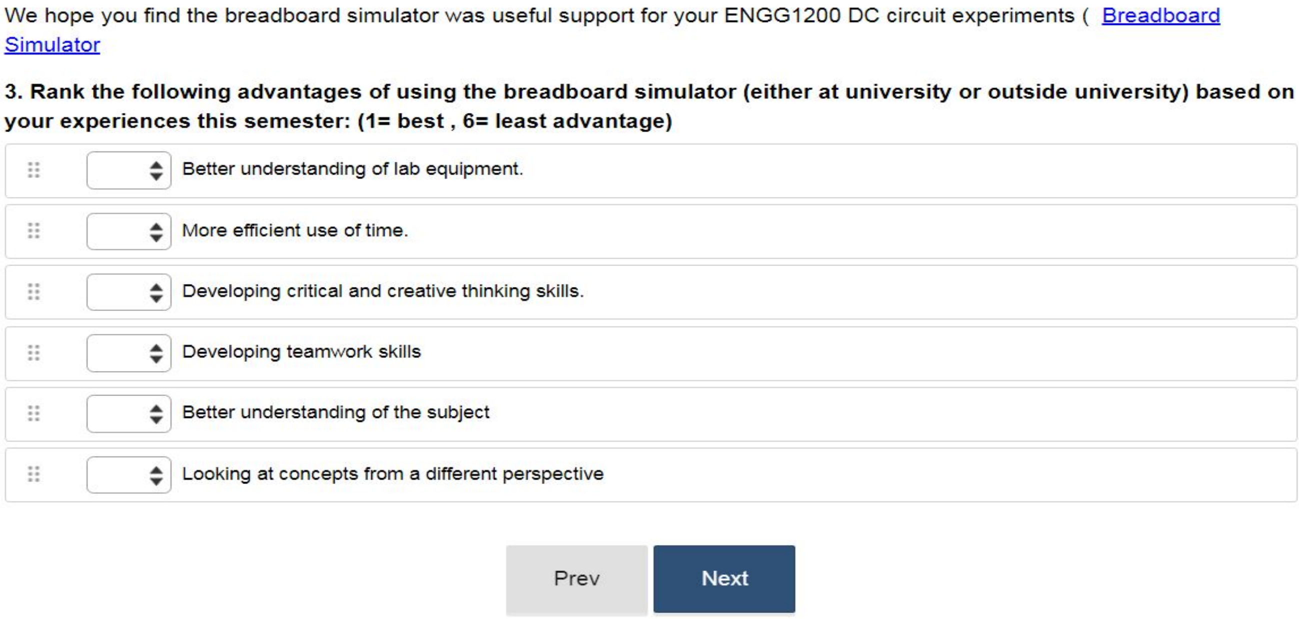
(Physical laboratories in this context refer to conventional, face-to-face laboratories)

	Strongly Agreed	Agreed	Neither	Disagreed	Strongly Disagreed
Physical laboratories help me to understand theory deeply.	○	○	○	○	○
Physical laboratories help me to develop the ability to design experiments.	○	○	○	○	○
Physical laboratories help me to understand and perform the experiment easily.	○	○	○	○	○
Physical laboratories improve teamwork.	○	○	○	○	○
Physical laboratories stress the importance of working safely with equipment.	○	○	○	○	○
Physical laboratories help me to improve my analytical abilities.	○	○	○	○	○
In physical laboratories, correct lab procedure is important in performing exercises.	○	○	○	○	○
The experience gained from physical laboratories are important for my career.	○	○	○	○	○
In physical labs, assistance and guidance from lab tutors are important.	○	○	○	○	○
Physical lab scheduling provides sufficient time to complete the experiment.	○	○	○	○	○
I have learnt how to effectively use lab equipment in physical labs.	○	○	○	○	○
I prefer to go to labs and lectures rather than learn on-line.	○	○	○	○	○
Physical labs provide students with the autonomy to deal with problems using innovative methods and get things done their own way.	○	○	○	○	○



2. These set of statements are related to the breadboard simulator (not physical lab) , your feedback is highly appreciated if can tell to what extent do you agree or disagree with the following statements?

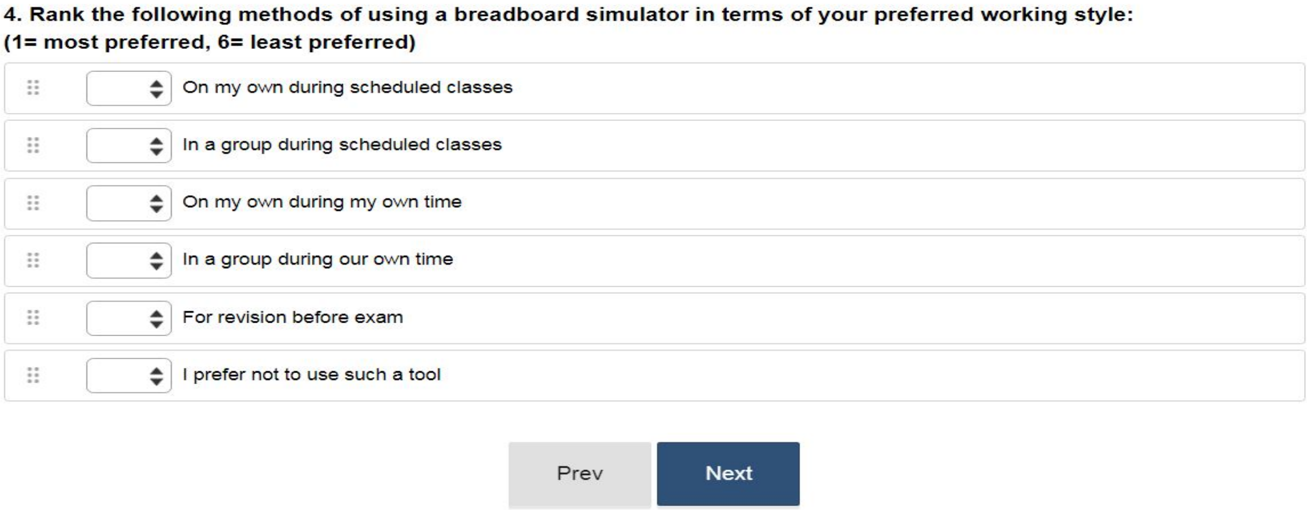
	Strongly Agreed	Agreed	Neither	Disagreed	Strongly Disagreed
Breadboard simulator helps me to understand theory deeply.	○	○	○	○	○
Breadboard simulator helps me to develop the ability to design experiments.	○	○	○	○	○
Breadboard simulator helps me to understand and perform the experiment easily.	○	○	○	○	○
Breadboard simulator improves teamwork.	○	○	○	○	○
Breadboard simulator stresses the importance of working safely with equipment.	○	○	○	○	○
I believe that, for advance topics in future, such a tool helps me to improve analytical abilities.	○	○	○	○	○
In breadboard simulator, correct lab procedure is important in performing exercises.	○	○	○	○	○
The experience gained from breadboard simulator are important for my career.	○	○	○	○	○
Use of breadboard simulator is disadvantage by unavailability of lab tutor assistance.	○	○	○	○	○
Breadboard simulator enable sufficient time to complete experiments.	○	○	○	○	○
I have learnt how to effectively use lab equipment in breadboard simulator.	○	○	○	○	○
I prefer on-line learning to lectures and labs.	○	○	○	○	○
Breadboard simulator provides students with the autonomy to deal with problems using innovative methods and get things done their own way.	○	○	○	○	○



We hope you find the breadboard simulator was useful support for your ENGG1200 DC circuit experiments (Breadboard Simulator

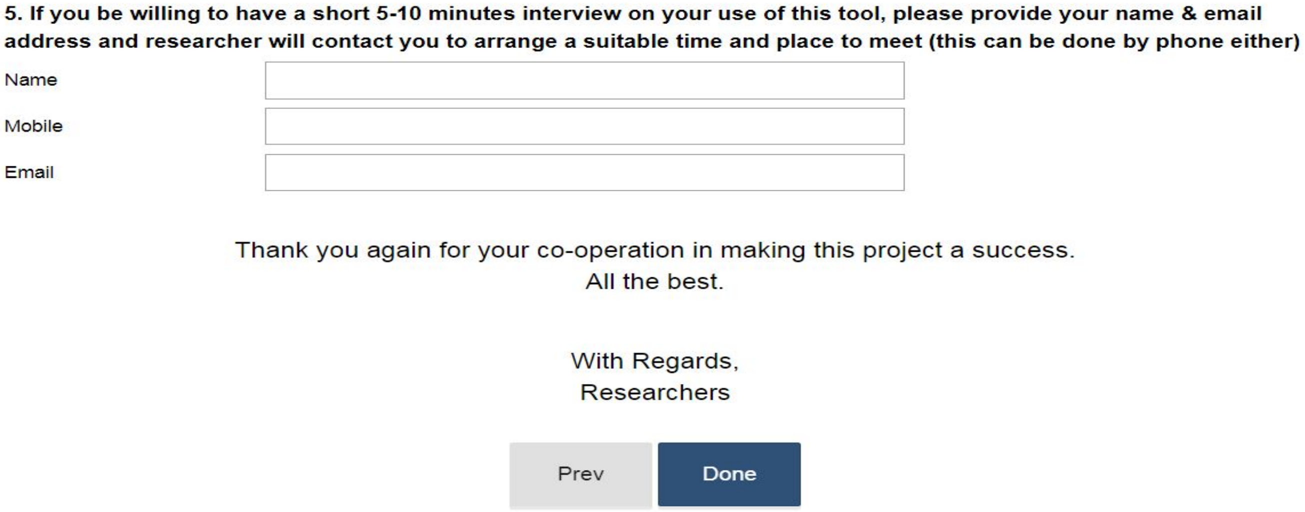
3. Rank the following advantages of using the breadboard simulator (either at university or outside university) based on your experiences this semester: (1= best , 6= least advantage)

Better understanding of lab equipment.
More efficient use of time.
Developing critical and creative thinking skills.
Developing teamwork skills
Better understanding of the subject
Looking at concepts from a different perspective



4. Rank the following methods of using a breadboard simulator in terms of your preferred working style: (1= most preferred, 6= least preferred)

On my own during scheduled classes
In a group during scheduled classes
On my own during my own time
In a group during our own time
For revision before exam
I prefer not to use such a tool



5. If you be willing to have a short 5-10 minutes interview on your use of this tool, please provide your name & email address and researcher will contact you to arrange a suitable time and place to meet (this can be done by phone either)

Name	
Mobile	
Email	

Thank you again for your co-operation in making this project a success.
All the best.

With Regards,
Researchers

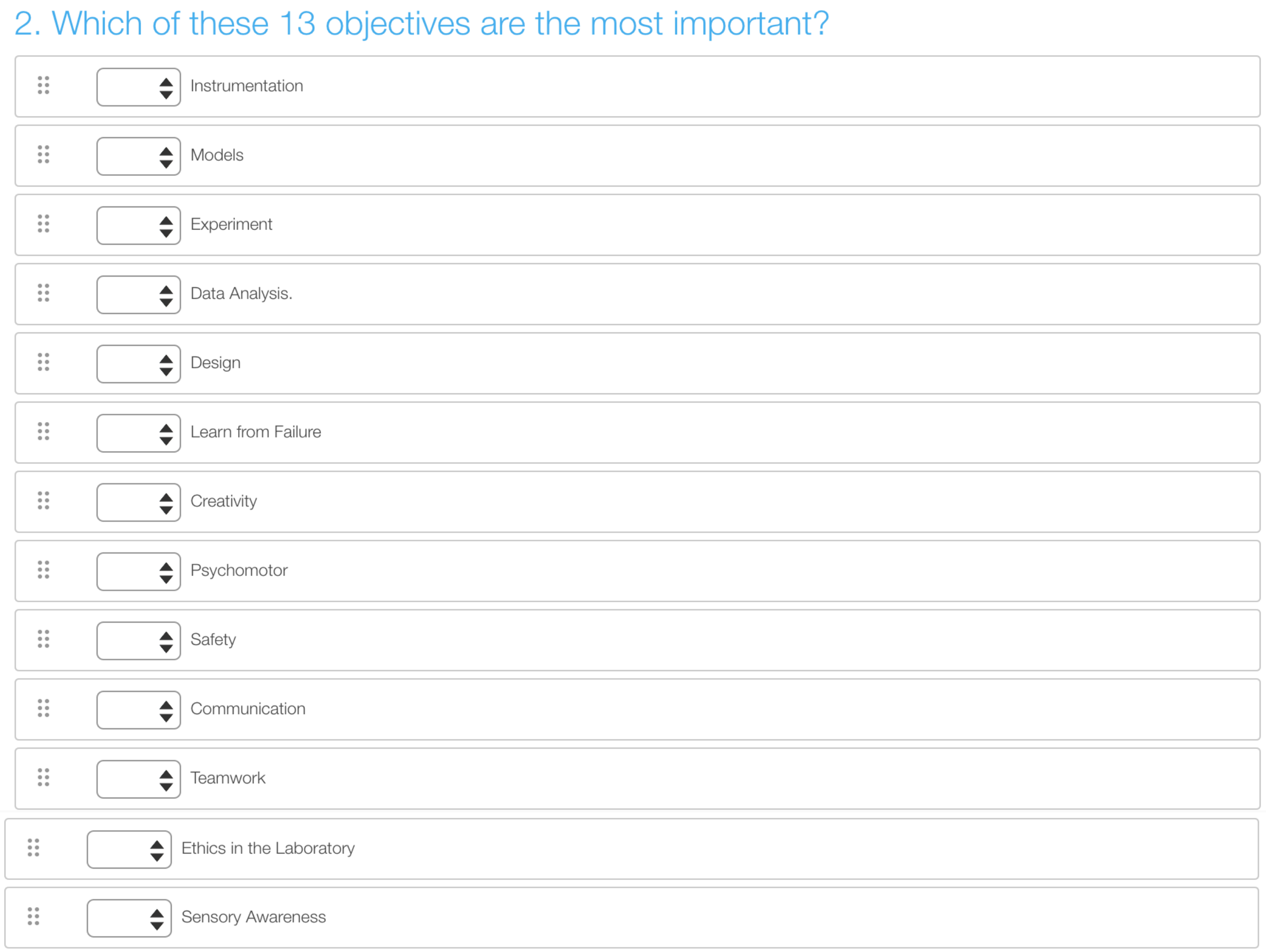
Appendix V - Interview with Academic Staff Form

Hello Dear,

This research project investigates the effectiveness of virtual laboratories.

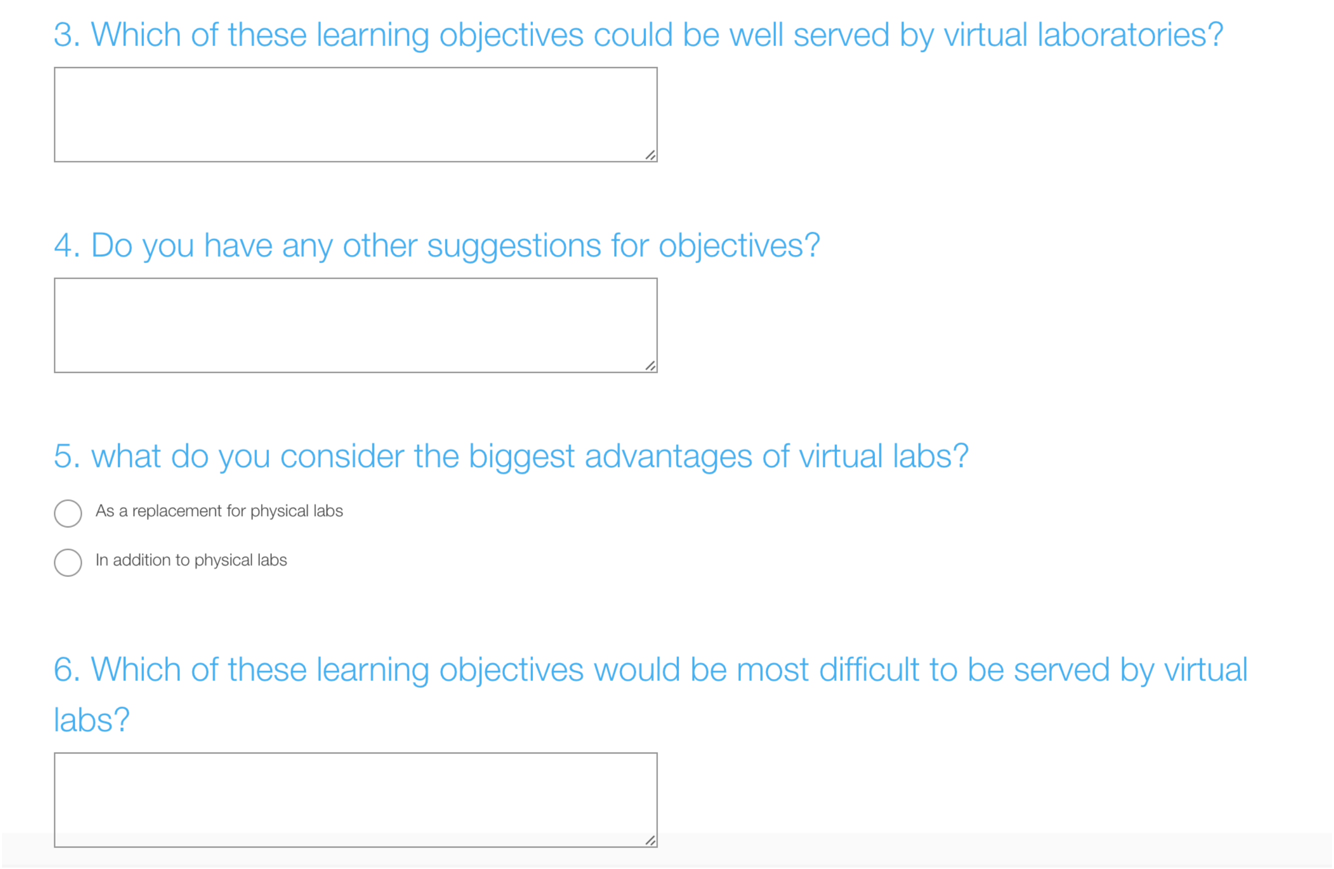
The best attempt to formulate a consolidated set of learning objectives for laboratories was based on a workshop organized on behalf of ABET (Accreditation Board for Engineering and Technology, in the USA) in 2002 (FEISEL and ROSA 2005). They proposed 13 objectives which are:

1: Instrumentation.
2: Models.
3: Experiment.
4: Data Analysis.
5: Design.
6: Learn from Failure.
7: Creativity.
8: Psychomotor.
9: Safety.
10: Communication.
11: Teamwork.
12: Ethics in the Laboratory.
13: Sensory Awareness.



2. Which of these 13 objectives are the most important?

- Instrumentation
- Models
- Experiment
- Data Analysis.
- Design
- Learn from Failure
- Creativity
- Psychomotor
- Safety
- Communication
- Teamwork
- Ethics in the Laboratory
- Sensory Awareness



3. Which of these learning objectives could be well served by virtual laboratories?

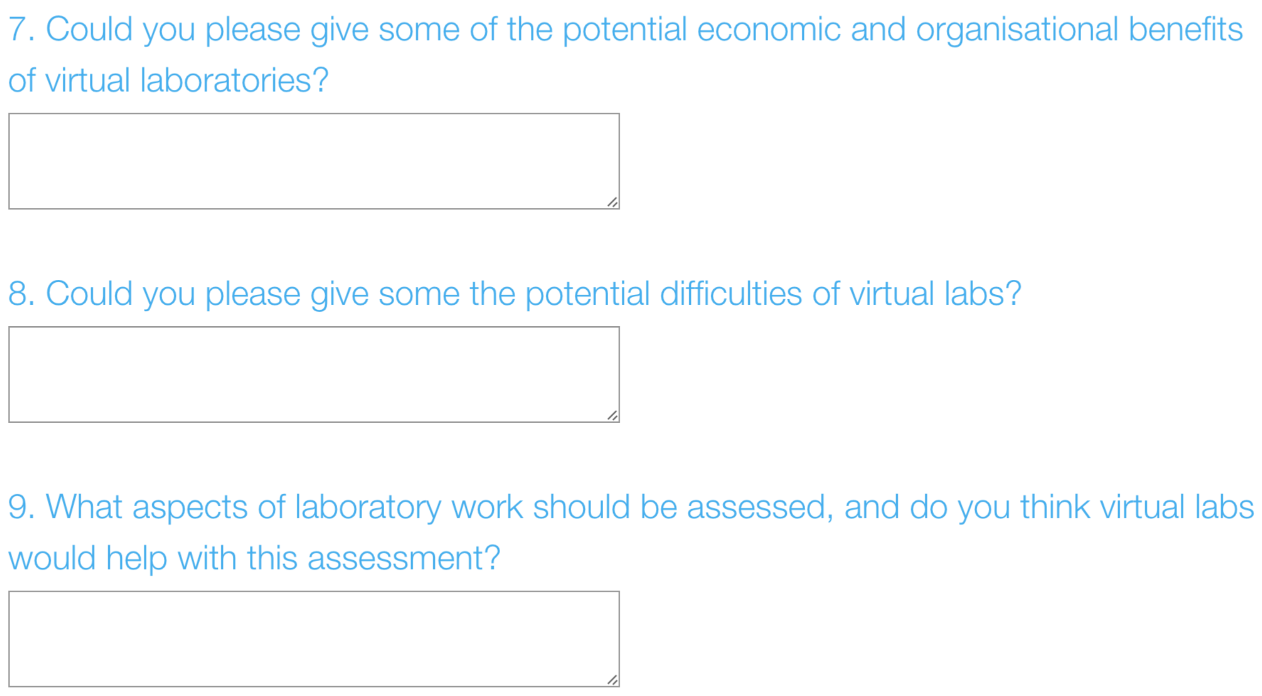
4. Do you have any other suggestions for objectives?

5. what do you consider the biggest advantages of virtual labs?

○ As a replacement for physical labs

○ In addition to physical labs

6. Which of these learning objectives would be most difficult to be served by virtual labs?



7. Could you please give some of the potential economic and organisational benefits of virtual laboratories?

8. Could you please give some the potential difficulties of virtual labs?

9. What aspects of laboratory work should be assessed, and do you think virtual labs would help with this assessment?

Appendix VI – Ethics Committee Application Approvals

SCHOOL OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING

ETHICS COMMITTEE

OUTCOME OF REVIEW

APPLICATION DETAILS:

Reference:	EC201409ALT
Name:	Ali Altalbe
Student Number:	43516955
Project Title:	Simulated Engineering Laboratory Work using Tablet Computer: Group work and Laboratory
Principal Advisor:	Neil Bergmann

Date Received:	
Expedited Review:	Yes
Date Reviewed:	

OUTCOME OF REVIEW:

X Approved	(Approval is for 12 Months)	Approved From: 31/10/2014	Approved To: 30/10/2015
☐ Request Amendment			
☐ Require Submission to BSSERC/MREC			

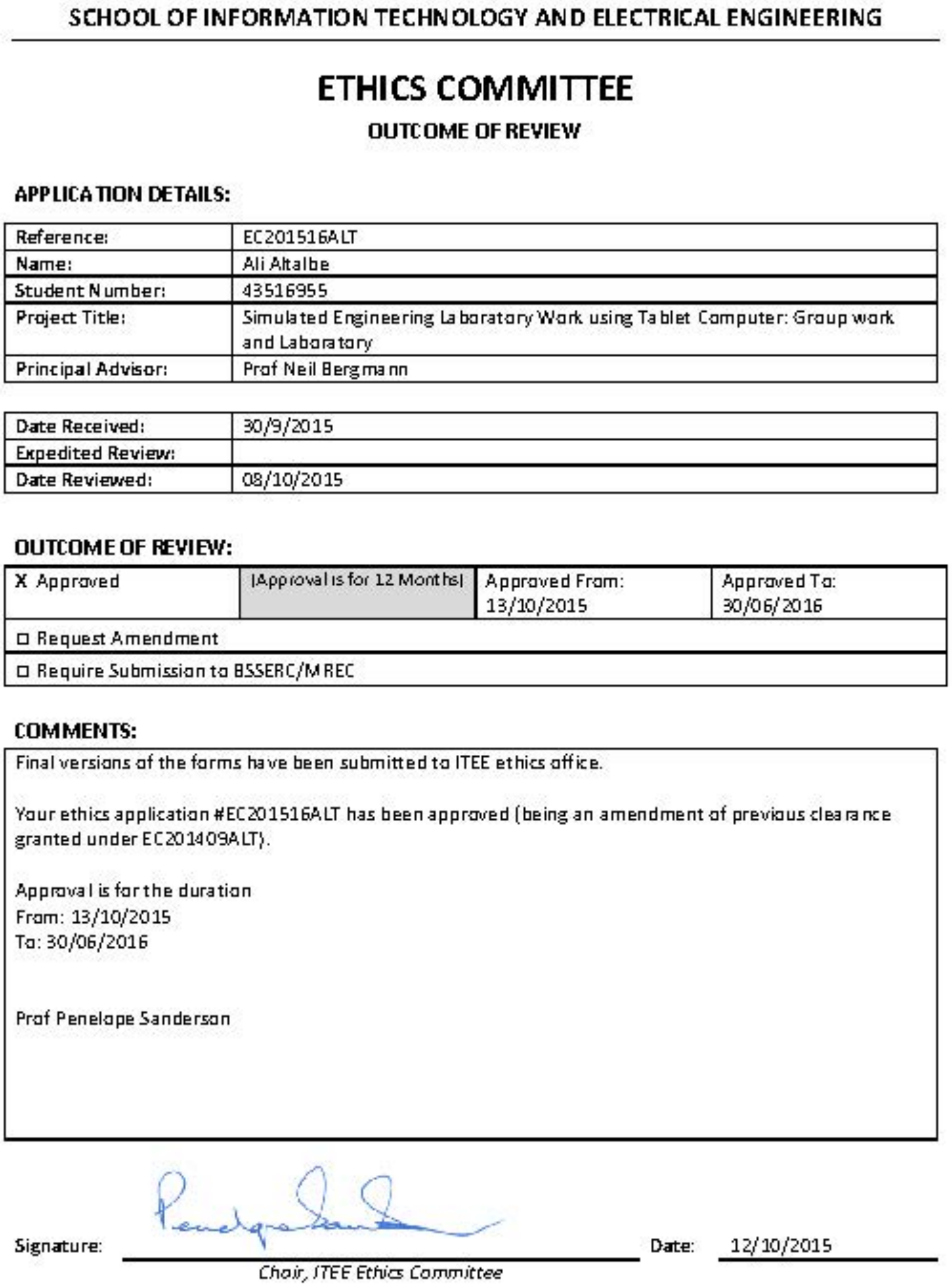
COMMENTS:

Final versions of the forms have been submitted to ITEE ethics office.

Approval is for 12 months:
FROM: *31 October 2014*
TO: *30 October 2015*

Stephen Viller
Acting Ethics Coordinator

Signature: ______________________ **Date:** 5/11/2014
Chair, ITEE Ethics Committee



SCHOOL OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING

ETHICS COMMITTEE

OUTCOME OF REVIEW

APPLICATION DETAILS:

Reference:	EC201516ALT
Name:	Ali Altalbe
Student Number:	43516955
Project Title:	Simulated Engineering Laboratory Work using Tablet Computer: Group work and Laboratory
Principal Advisor:	Prof Neil Bergmann

Date Received:	30/9/2015
Expedited Review:	
Date Reviewed:	08/10/2015

OUTCOME OF REVIEW:

X Approved	(Approval is for 12 Months)	Approved From: 13/10/2015	Approved To: 30/06/2016
☐ Request Amendment			
☐ Require Submission to BSSERC/MREC			

COMMENTS:

Final versions of the forms have been submitted to ITEE ethics office.

Your ethics application #EC201516ALT has been approved (being an amendment of previous clearance granted under EC201409ALT).

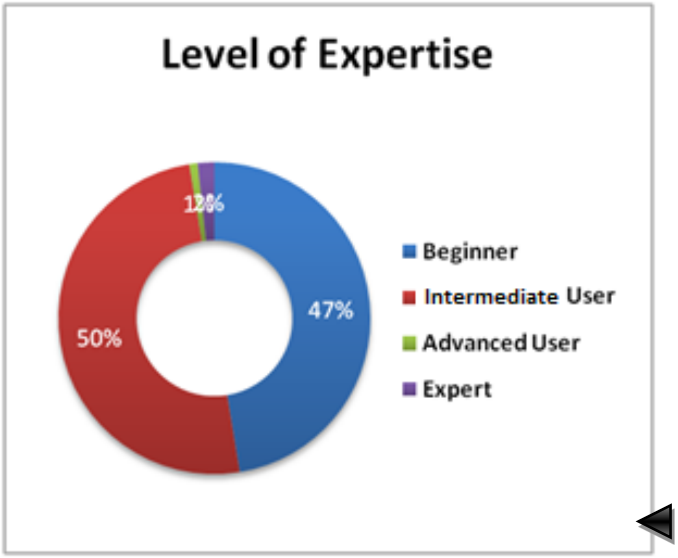
Approval is for the duration
From: 13/10/2015
To: 30/06/2016

Prof Penelope Sanderson

Signature: Penelope Sanderson Date: 12/10/2015

Chair, ITEE Ethics Committee

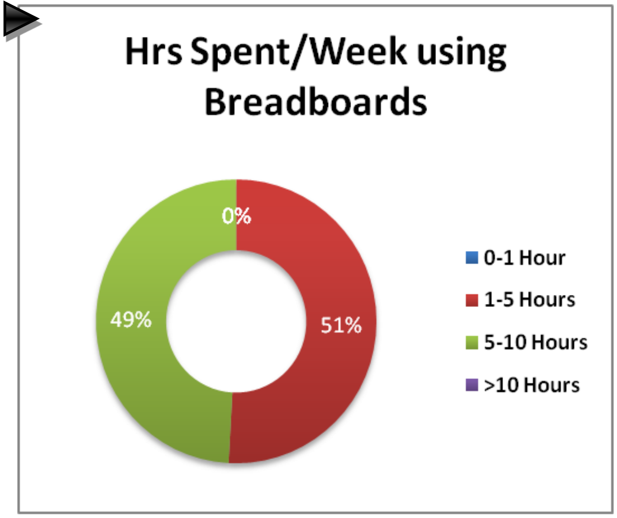
Appendix VII – Demographics from Post-Development Survey



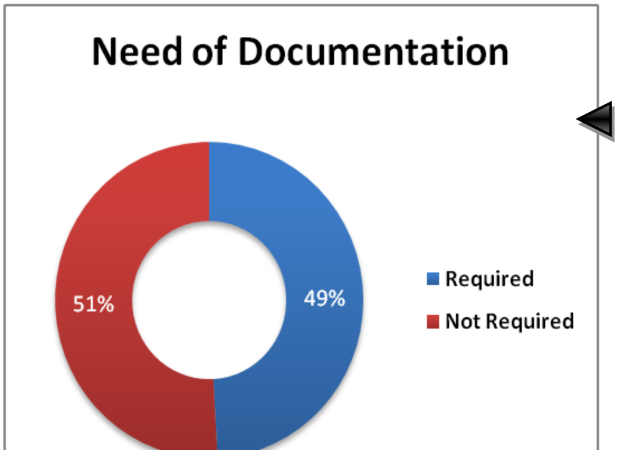
Demographics and additional findings from the second survey are presented. The demographic of second survey comprises of users who spent an average of 5 hours per week using breadboards during course module number ENGG1300, use the Google Chrome browser and have an intermediate level of expertise. The general response is that there is greater need for documentation, that the user-interface highly user-friendly, and that there weren't many instances of technical failure (crashes/freezes) of the application.

Here, it can be seen that the majority of the participants in the study do not possess much experience in using laboratory equipment at University of Queensland relevant to the course module ENGG1300 in semester 2 (2015).

Further, the time they spent using breadboards in laboratory during ENGG1300 is centered around 5 hours per week.

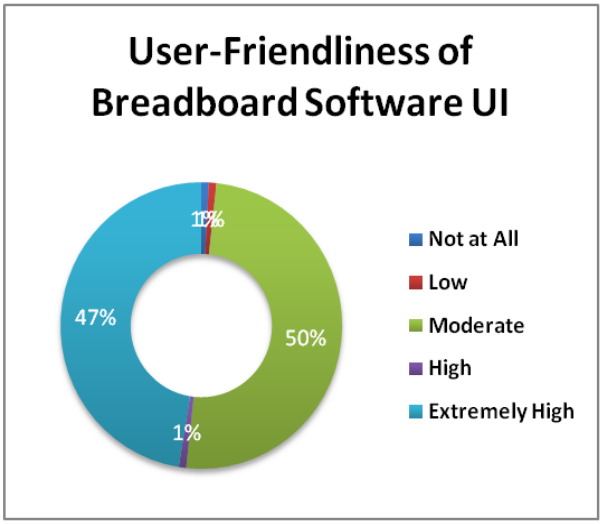


All the respondents use Google Chrome as the browser for connecting to internet to access the virtual simulator.



Opinion is divided over whether the software requires documentation. It will be better to include at least some basic documentation for the software which researcher did later.

In gathering opinions on user-friendliness of software user-interface, nearly all the responses ranged from moderate to extremely high. The general conclusion that can be drawn therefore, is that users are satisfied with the software user-interface.

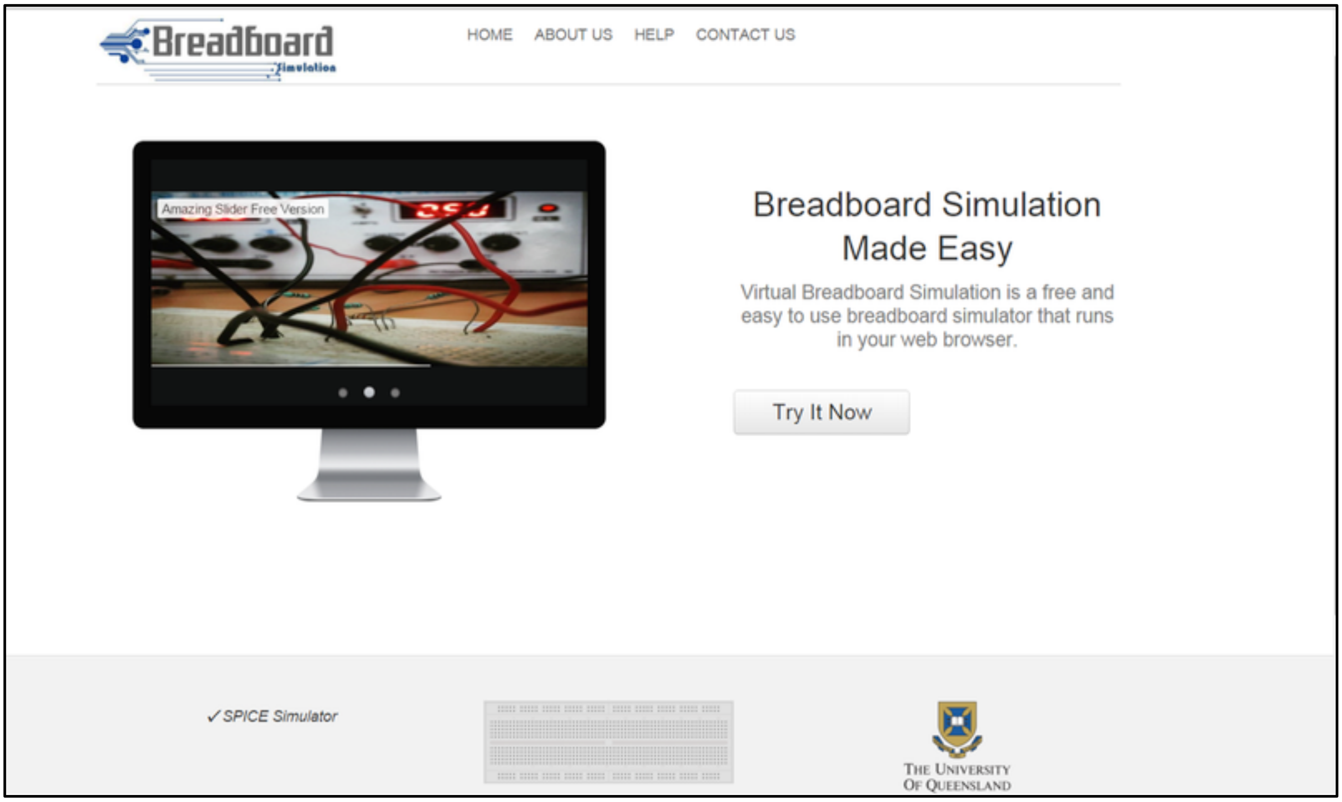


With almost all the users reporting that software rarely crashes/freezes, reliability of the software can be judged as good.

Appendix VIII – Screen Shots of the Breadboard Website

This appendix contains the screen shots from the Breadboard Simulator website. This includes the home page, introduction, components pages and contact page.

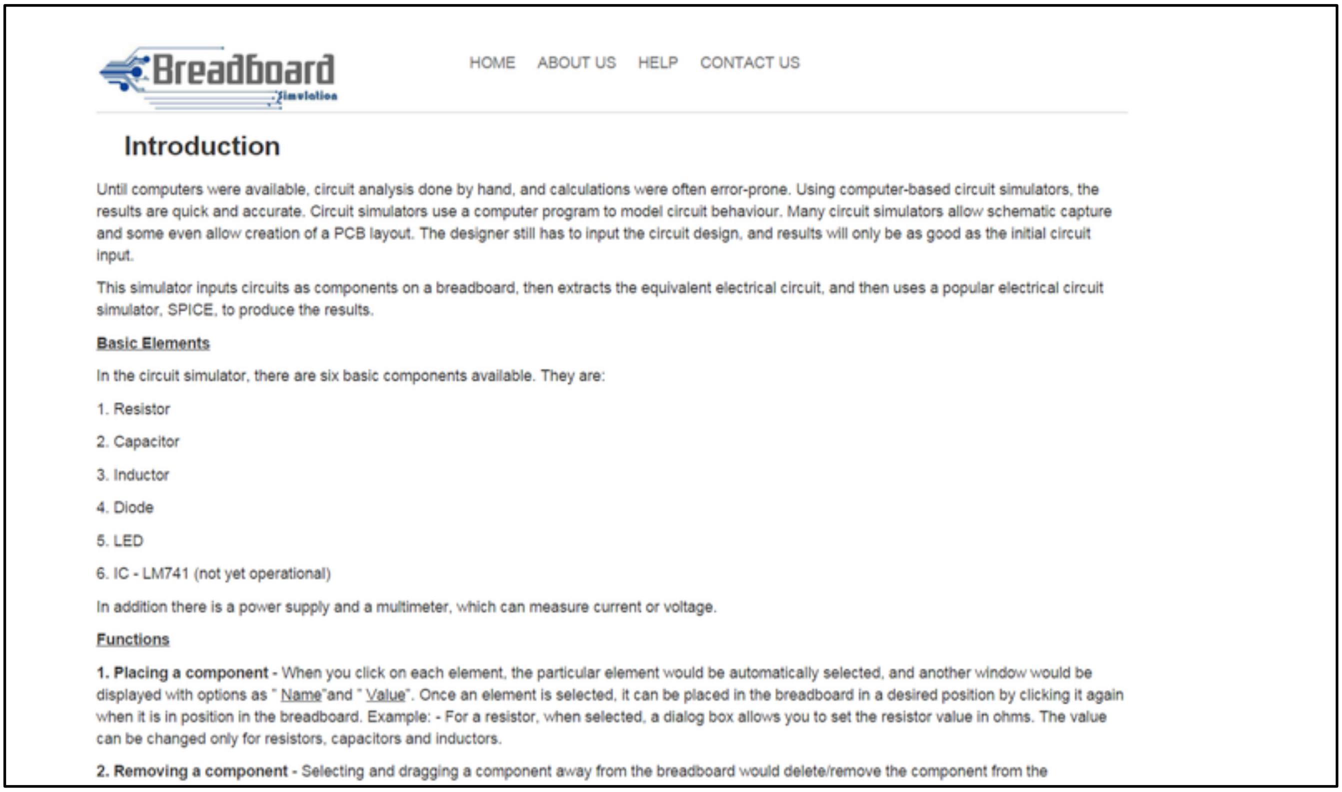
Home Page



Breadboard Simulation Made Easy

Virtual Breadboard Simulation is a free and easy to use breadboard simulator that runs in your web browser.

Introduction Page



Introduction

Until computers were available, circuit analysis done by hand, and calculations were often error-prone. Using computer-based circuit simulators, the results are quick and accurate. Circuit simulators use a computer program to model circuit behaviour. Many circuit simulators allow schematic capture and some even allow creation of a PCB layout. The designer still has to input the circuit design, and results will only be as good as the initial circuit input.

This simulator inputs circuits as components on a breadboard, then extracts the equivalent electrical circuit, and then uses a popular electrical circuit simulator, SPICE, to produce the results.

Basic Elements

In the circuit simulator, there are six basic components available. They are:

1. Resistor
2. Capacitor
3. Inductor
4. Diode
5. LED
6. IC - LM741 (not yet operational)

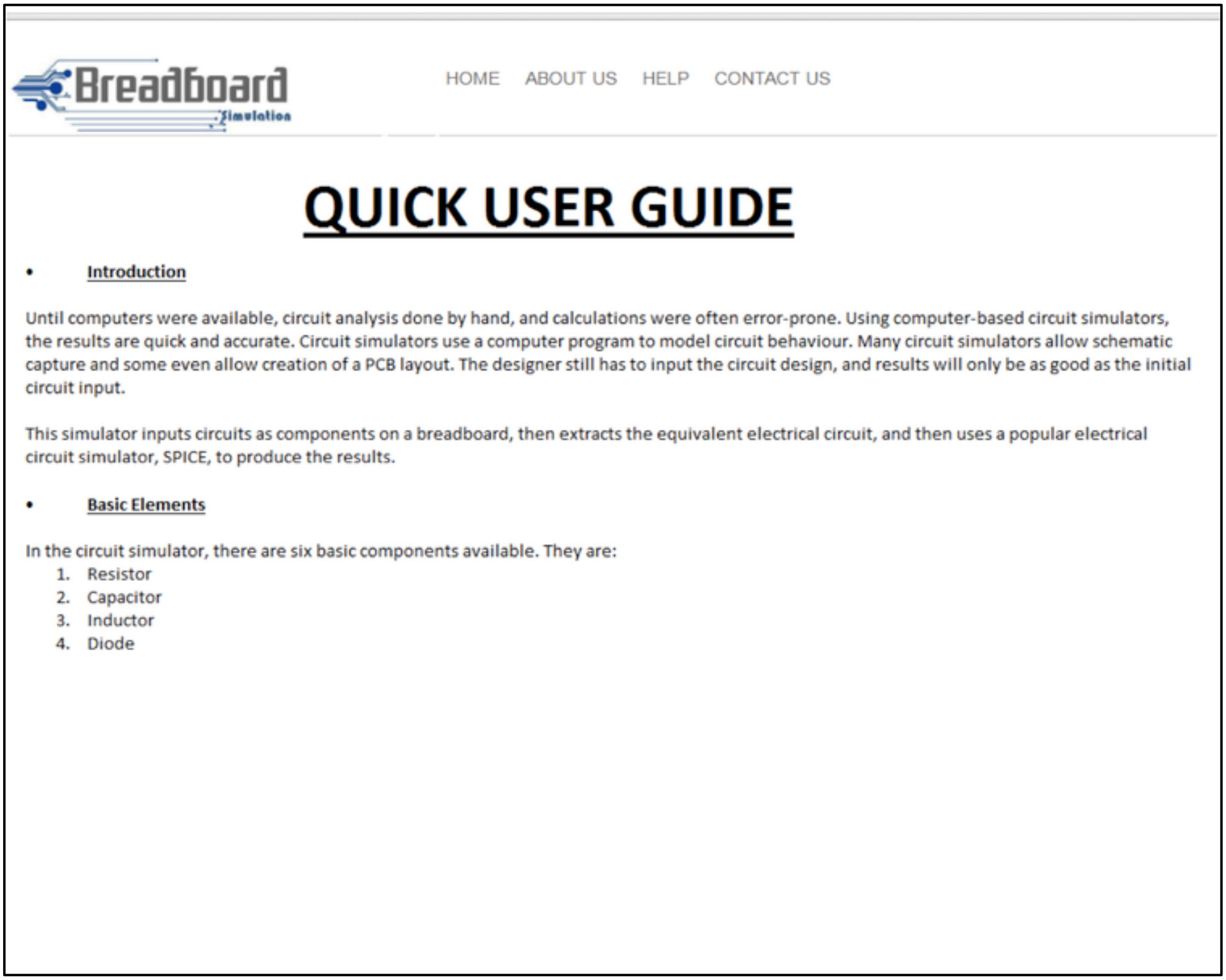
In addition there is a power supply and a multimeter, which can measure current or voltage.

Functions

1. Placing a component - When you click on each element, the particular element would be automatically selected, and another window would be displayed with options as " Name"and " Value". Once an element is selected, it can be placed in the breadboard in a desired position by clicking it again when it is in position in the breadboard. Example: - For a resistor, when selected, a dialog box allows you to set the resistor value in ohms. The value can be changed only for resistors, capacitors and inductors.

2. Removing a component - Selecting and dragging a component away from the breadboard would delete/remove the component from the

User Guide



QUICK USER GUIDE

- **Introduction**

Until computers were available, circuit analysis done by hand, and calculations were often error-prone. Using computer-based circuit simulators, the results are quick and accurate. Circuit simulators use a computer program to model circuit behaviour. Many circuit simulators allow schematic capture and some even allow creation of a PCB layout. The designer still has to input the circuit design, and results will only be as good as the initial circuit input.

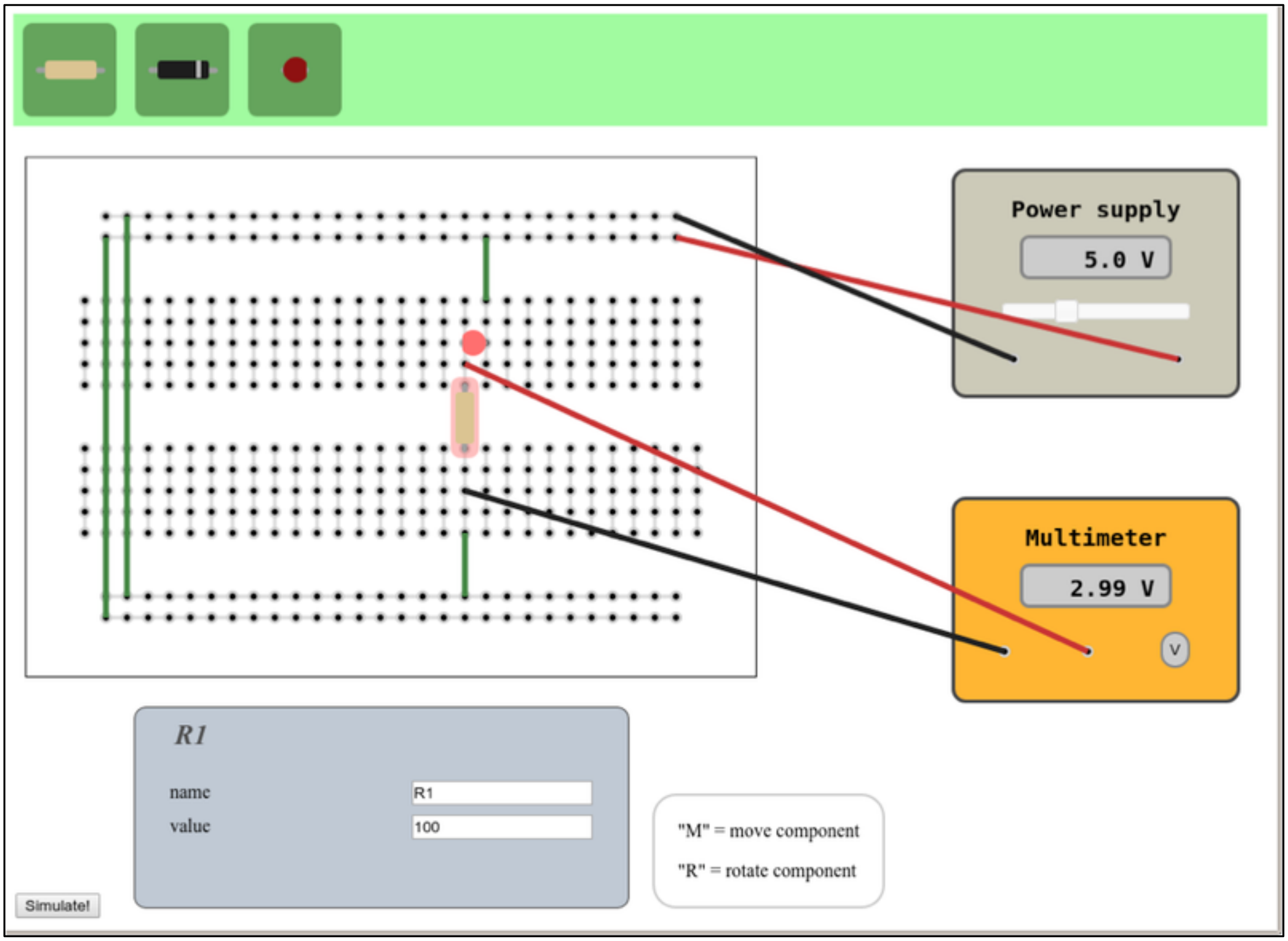
This simulator inputs circuits as components on a breadboard, then extracts the equivalent electrical circuit, and then uses a popular electrical circuit simulator, SPICE, to produce the results.

- **Basic Elements**

In the circuit simulator, there are six basic components available. They are:

1. Resistor
2. Capacitor
3. Inductor
4. Diode

Initial Components and Design



Power supply
5.0 V

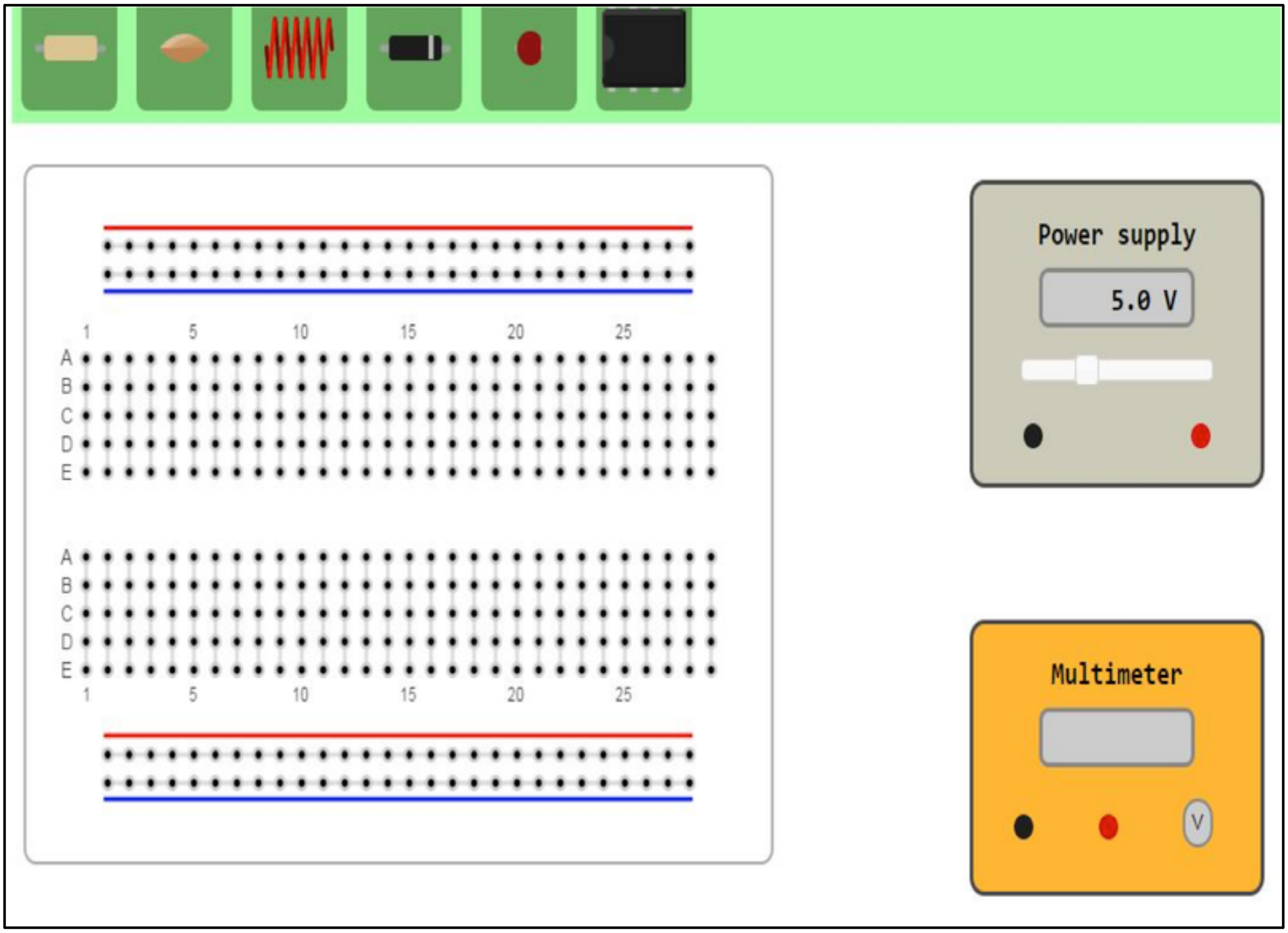
Multimeter
2.99 V

R1

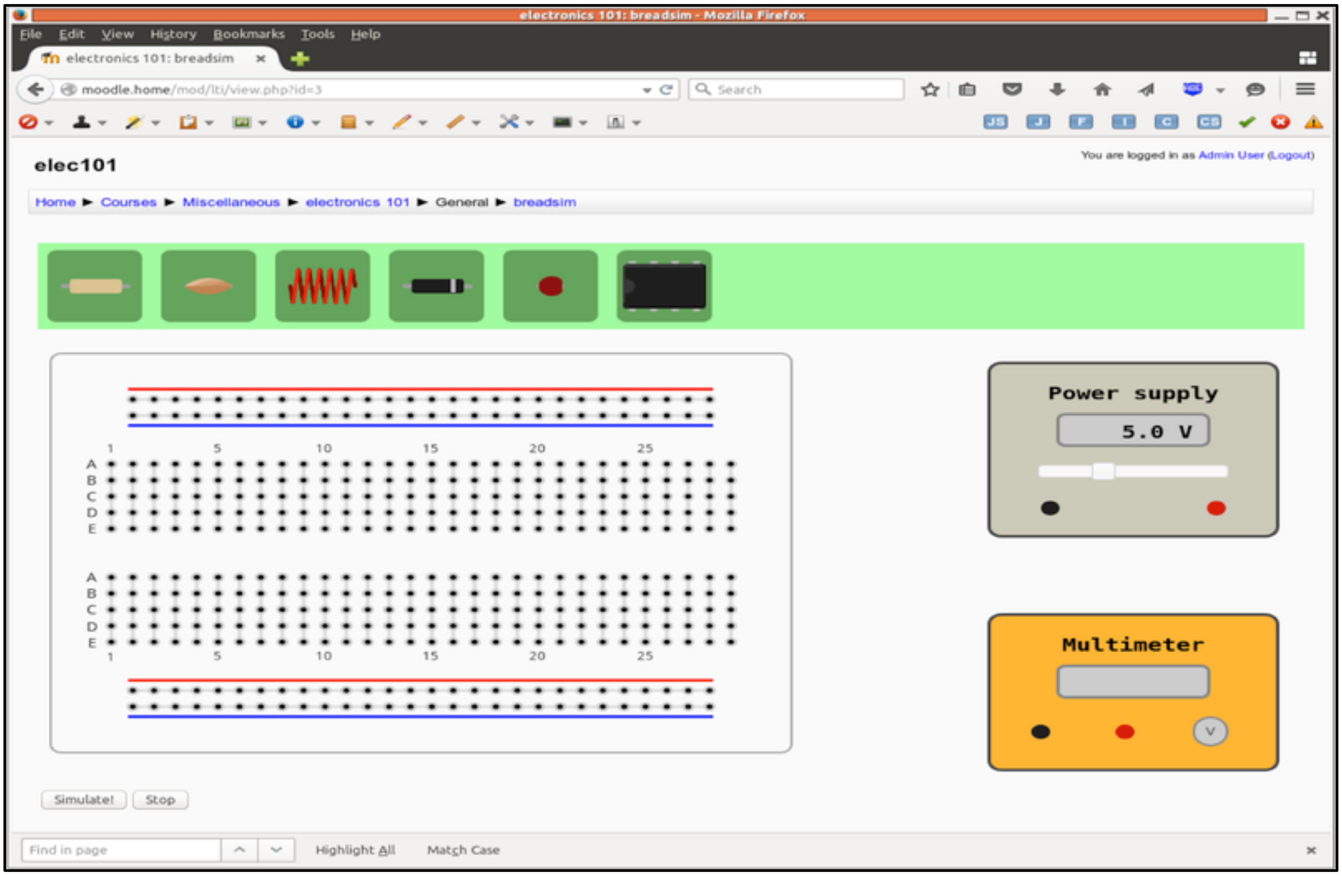
name R1
value 100

"M" = move component
"R" = rotate component

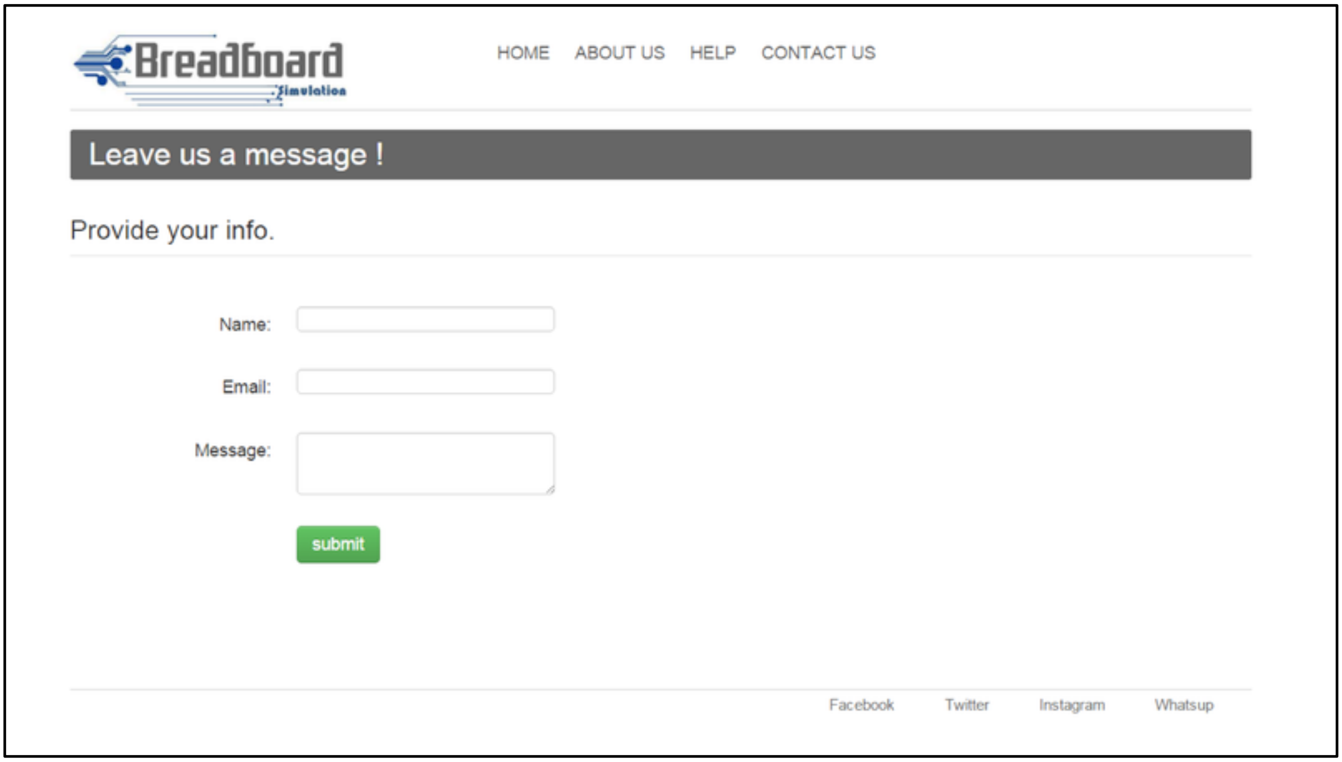
Full Components



Integration with Moodle



Contact Page



Leave us a message !

Provide your info.