DESIGN, IMPLEMENTATION AND EVALUATION OF A NOVEL BIOMEDICAL ENGINEERING INSTRUMENTATION COURSE AT MAKERERE UNIVERSITY - KAMPALA, UGANDA

by

Henry Fenekansi Kiwumulo

Department of Biomedical Engineering

Duke University

Date: _______________________

Approved:

____

Prof. Kathryn Nightingale, Supervisor

____

Prof. William Reichert

____

Dr. Robert Ssekitoleko

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Abstract

Uganda is increasingly dependent upon imported biomedical pieces of equipment to support patient care and health related research. Most of this equipment arrives without the accompanying documentation, maintenance and support. In many cases, the equipment specifications are not suited to the local environment, which affects the durability and use of this equipment. The unfortunate result creates a vast array of medical equipment that lie about in various states of disrepair. Additionally, given the uniqueness of the environment and people in Africa, there is a need to design biomedical equipment that is suited to both the people and the environment. Although the graduates of the Makerere BME program participate in research, innovation and design of such low resource settings devices, these graduates lack a novel BME instrumentation course to implement their amazing innovations. This research thesis comes in to solve this dilemma by investigating economically effective lab components and skills necessary for designing such a course which will help grow the BME discipline and the institutional regional capacity to do basic science research.

The first chapter of this research comments about the medical equipment situation in Uganda in addition to the BME program in Makerere University. This chapter provides the researcher's motivation and hypothesis for carrying out this research.

The second chapter of this research focuses on the Duke BME instrumentation labs. This chapter concentrates on the 9 labs that the researcher carried out at Duke University and how such labs can gainfully be translated to the Makerere BME instrumentation course.

The third chapter deals with a discussion of the instrumentation laboratory and course experience that has been available to the BME majors at Makerere to date. This discussion involves results generated by a survey taken from the BME students who have just completed this course and those who have already graduated.

The fourth chapter discusses the current status and the researcher's proposed BME lab design. Additionally, this chapter highlights the human resource, the current lab space dimensions, the furniture and fittings, the training equipment, lab reagents and consumables.

The fifth chapter comments about the BME instrumentation course currently piloted at Makerere University. This chapter represents the progress of the first offering of the new BME instrumentation course taught at Makerere University that was designed this past summer following the Duke course model.

Finally, the last chapter six serves as the conclusion chapter for this thesis work. This chapter briefly analyzes the strengths, weaknesses, opportunities and threats (SWOT) for the current Makerere University BME instrumentation course. The chapter finally provides some critical findings and thereafter provides some recommendations and the future work.

Dedication

Dedicated to my dear wife Barbara and lovely daughters – Christina and Mary.

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Many thanks to my supervisor – Prof. Kathy Nightingale whose dedicated guidance has always inspired and allowed me to move on. Great thanks to my scholarship director – Prof. William Reichert who has always steered my comfortable progress by providing all the necessary resources. My sincere gratitude also goes to my BME program head Dr. Robert Ssekitoleko whose excellence has always driven my hard work. Finally, I feel highly indebted to Mr. Matt Brown – my Duke BME lab instructor, the amazing Duke BME department and the entire Duke University fraternity for the encouragement and support during my stay at Duke University. May God bless you so much for this support.

CHAPTER ONE - INTRODUCTION

1.0 INTRODUCTION

This chapter comments about the medical equipment situation in Uganda in addition to the BME program at Makerere University. This chapter also provides an introduction to the researcher's motivation and the problem statement for carrying out this research.

1.1 BME offering institutions in Sub-Saharan Africa

The table below indicates 20 BME offering institutions in the Sub-Saharan African region [1]. All these institutions have a common goal of training biomedical engineers that can reduce the accumulation of routine medical instrumentation that lies unused or in disrepair due to a lack of skilled workforce and/or readily available spare parts. Unfortunately, most of these institutions do not provide an online curriculum that could help analyze the instrumentation courses offered. Uganda has 3 institutions currently emerging with the BME program in addition to the one at Makerere University. Three of the 4 curricula from these Ugandan BME institutions have been analyzed and found with no BME instrumentation lab component. The BME instrumentation courses in such institutions involve bringing faulty medical equipment which students analyze and try to repair. I hypothesize that this faulty equipment method would be more rewarding and successful if the students were able to design and build circuits for such equipment.

A verbal discussion carried out with the program coordinators from the above institutions indicated three key issues. [2] The first issue was the lack of reference course models that would help in designing concrete BME instrumentation courses to facilitate the Ugandan healthcare. The second issue was in line with the newness of these programs to such institutions. Apart from Makerere, the other three institutions had not yet implemented an instrumentation course and had nothing for comparison. The third issue emerged from the limited BME professionals that would help advise and improve the above curricula.

Table 1: Sub-Saharan BME institutions[1]

Institution	Country	BME degree offered	Curriculum accessibility
Makerere University	Kampala, Uganda	BS	YES
Mbarara University of Science and Technology	Mbarara, Uganda	BS	YES
Kyambogo University	Kampala, Uganda	D, BS	NO
Earnest Cook Ultra-sound Research Education Institute (ECUREI)	Kampala, Uganda	D, BS	YES
University of Witwatersrand	Johannesburg, Republic of South Africa	BS	NO
University of Cape Town	Cape Town, Republic of South Africa	MS, PhD	NO
University of Pretoria	Pretoria, Republic of South Africa	MS, PhD	NO
University of Lagos	Lagos, Nigeria	BS, MS	NO
Addis Ababa	Addis Ababa,	BS, MS	NO

Institute of Technology	Ethiopia		
University of Ghana	Accra, Ghana	BS, ME, MP, PhD	NO
Valley View University	Adentan, Ghana	C, D, BS	NO
Technical University Mombasa	Mombasa, Kenya	C, D, BS, BT	NO
Kenyatta University	Nairobi, Kenya	BS	NO
Malawi University of Science and Technology	Thyolo, Malawi	BS	NO
University of Malawi, The Polytechnic	Blantyre, Malawi	D, BS	NO
Bells University of Technology	Ota, Nigeria	BE	NO
Federal University of Technology, Owerri	Owerri, Nigeria	BT, MS, PhD	NO
Jimma University	Jimma, Ethiopia	BS	NO
All Nations University	Koforidua, Ghana	BS	NO
Kwame Nkrumah University of Science and Technology	Kumasi, Ghana	BS	NO

D Diploma, C Certificate, BE Bachelor of Engineering, BS Bachelor of Science, BT Bachelor of Technology, MS Masters of Science, ME Masters of Engineering, MP Masters of Philosophy, PhD Doctoral degree.

This research comes in to solve some of the above gaps in the instrumentation course curriculum. In this work, I have introduced the Duke BME instrumentation course model into the Makerere BME curriculum, with specialized BME labs like the body temperature measurement, calibration lab (lab 3) and the pulse plethysmography lab

(lab 9) which allow the students to build actual biomedical devices, providing the students with proficiency in designing, implementing, and trouble-shooting problems in biomedical instruments. This model will additionally modify the existing instrumentation labs by matching the theoretical lecture notes with the lab activities for a better conceptual understanding by the students.

At Makerere, prior to the introduction of the medical instrumentation course developed in this thesis, BME students have been taking an introductory ECE course. While there is some common material, the new BME course has been tailored to the expected background of the incoming BME students and the laboratory exercises are focused on biomedical instrumentation applications. The table below indicates the relevant labs from the ECE course and the action taken in the new course. These ECE labs lack a BME instrumentation component which serves as a key to the BME students as they prepare for their design classes. In the BME course, labs are included that address these fundamental concepts but that are tailored to applications of medical instrumentation and that match the theoretical BME lectures for a better students' understanding. For example, the "Two port network and a hybrid model" lab has been excluded because it is more specialized to the Telecommunication engineering students than the BME students. Chapter two describes the detailed Duke BME labs and how they have been implemented to improve the BME instrumentation course.

Table 2: showing the existing ECE labs done by BME students and the action to take

LAB	ACTION
Measurement of different Circuit parameters	Modify
Verifying Kirchhoff current and voltage laws	Modify
Mesh analysis	Modify
Maximum power transfer and transformers	Modify
RC Circuit analysis	Modify
Two port network and a hybrid model	Remove
Operational amplifiers and Diodes	Modify

1.2 Medical equipment situation in Uganda

Uganda is increasingly importing complex pieces of equipment to support health and health related research. Most of these pieces of equipment arrive without accompanying care, maintenance and support. In some cases, the equipment specifications are not suited to the local environment, which affects durability and use of this equipment. The maintenance of medical equipment is essential to ensure that it functions correctly and efficiently and ultimately to ensure proper clinical management of the patient. It is, therefore, important that adequate standards of maintenance are achieved. Yet, in some countries like Uganda, "more than 60% of biomedical equipment is not used because of lack of facilities for maintenance and repair" [3]. These problems have no simple solution, and their implications are far wider than those associated with the maintenance of an individual piece of equipment.

Equipment maintenance is usually carried out by either - laboratory and hospital personnel employed to operate the instrument, service personnel employed within a hospital service department, technicians with special knowledge of a particular instrument, or engineers with specialist expertise. Maintenance aims at ensuring that the equipment attains the standard performance characteristics set by the hospital, the manufacturer's specification, and the clinical requirements. Maintenance should be carried out on a preventive basis rather than after a breakdown. Unfortunately, Ugandan equipment normally experience major breakdowns which represents a failure sign in the maintenance and servicing programmes. [4]

Fundamental training is essential for the equipment operators and for the hospital maintenance staff so that the hospital may become nearly self-sufficient and able to keep its equipment in good working order. Good maintenance and servicing should be carried out as a partnership between the hospital and the manufacturer. Inevitably, however, the smaller the input by the manufacturer, the greater must be the input by the hospital. In Uganda, the manufacturers' presence, or that of their agents, is minimal and so also is their support. The level of support should be ascertained and taken into account during the process of instrument selection and purchase.

Some manufacturers offer contracts to lend equipment-even free of charge-but often the user has to agree to use reagents produced and sold by the same company. Quite often, their cost, in the long term, far exceeds the cost of purchasing other equipment and reagents. However, the cost of the reagents can be spread over a longer period of time. When the final equipment purchase decision is made, some installation problems are not normally considered. For example, the electrical supply compatibility with the instrument requirements including the necessary stability is rarely considered, other necessary services like gas and water supplies that must be available in appropriate quantity and quality are usually missing, unsuitable operating environment (temperature and humidity control), inadequate level of lighting, and insufficient working space especially with bulky equipment (like X-ray equipment and some laboratory analyzers) – additionally, there is often a lack of instrument transport facilities to their working area for example stairways, elevators, doorways and appropriate lifting gear.[5]

Selection, purchase, and installation of equipment must be primarily the responsibility of the head of the department and his or her staff. In making such decisions, both the capital and running costs must be taken into account. When choosing equipment, account should be taken of the availability of spares and the supplier's willingness to train the hospital staff appropriately. Unfortunately, it is only too frequent that equipment has to be abandoned because its running costs have not been budgeted for due to poor selection criteria. Often purchasing decisions are made outside the laboratory, for political or other non-specific reasons, and this contributes to the numerous pieces of medical and paramedical equipment that are not used effectively in Uganda. [6,7]

1.3 Makerere University BME program

This rapid growth of healthcare systems and the indispensable increasing role of technology in diagnostic, therapeutic, and associated research activities culminated into an increasing demand for skilled biomedical engineers in Uganda which led to the establishment of a biomedical engineering program in Makerere University in 2011. The graduates from this program are expected to use their knowledge acquired to reduce the costs of maintenance, waste, and loss of work hours from equipment downtime and other resources due to the current lack of this cadre of trainees on the market. Additionally, these graduates are expected to be in advisory sourcing positions, procurement and preventive maintenance correctly specified for our environment thus making further savings to the country.
The program graduates are also expected to have an in depth understanding of the subject thus creating a trainable group of resource persons. This trainability would make the biomedical engineers an easy group to retool especially with the purchase of new pieces of equipment hence matching with the rapid changes seen in the field of biomedical engineering and the need to keep up with global technology trends. Given the uniqueness of the environment and people in Uganda, this program identified a need to design biomedical equipment that is suited to both – the environment and the

people. The graduates from this program are expected to participate in research, innovation and design of new devices suited to and in response for the local need of healthcare in low resource settings.

1.3.1 Objectives and Educational Outcomes

The educational objectives of this programme are to:

- Produce graduates who are able to practice biomedical engineering to serve Uganda and the regional industries, government agencies, or national and international industries.
- Produce graduates with the necessary background and technical skills to work professionally in one or more of the following areas: medical imaging, health informatics, biomechanics, biomaterial/tissue engineering and medical instrumentation.
- Prepare graduates for personal and professional success with awareness and commitment to their ethical and social responsibilities, both as individuals and in team environments.
- Prepare graduates who are capable of entering and succeeding in an advanced degree program in a field such as engineering, science, or business.

1.4 Conclusion

Problem statement

Unfortunately, given the above Ugandan equipment status and the educational objectives of the BME program, there is still a gap in equipping the Makerere University students with the necessary instrumentation skills that can match with the rapid influx of this type of equipment in the Ugandan healthcare systems. Amongst the many reasons for this gap, one of the key reasons lies in the lack of a novel BME instrumentation course with a frugal BME lab that can help these students to practically appreciate what is theoretically taught in class. This research thesis comes in to design a laboratory based course that can solve this challenge and provide the necessary BME training for the design classes to be covered in third and fourth years.

CHAPTER TWO – DUKE BME LABORATORIES

2.0 DUKE BME LABORATORIES

Introduction:

Duke's Biomedical Engineering (BME) program is consistently ranked as one of the top biomedical engineering programs in the World. Duke BME combines a hands-on educational experience and an interdisciplinary research environment that prepares graduates to be leaders in integrating engineering and biology to detect and treat human diseases. This BME program offers students an opportunity to learn biomedical engineering concepts and methods from leading researchers in the field while also allowing students to understand the interaction between cutting edge research and commercial development of technology. The following are some of the state of the art laboratory resources where students interact and develop great ideas for different projects. [8]

- Tissue Properties and Orthopedic Laboratory
- Optics and Biosensors Laboratory
- Instrumentation Laboratory
- Ultrasonic Laboratories
- Cardiac Stimulation and Simulation Laboratory
- Experimental Electrophysiology Laboratory

- Cellular and Molecular Imaging Laboratory

Duke anticipates many undergraduate biomedical engineering (BME) students to seek jobs in industry after graduation and therefore ensures a learning environment that exposes these students to modem tools and equipment that best prepare them for an industrial setting. These BME laboratory courses use PC and non PC-based virtual instruments to prepare students for real-world experience with minimal cost and risk. [3] This thesis study concentrates on the Duke instrumentation lab and will review different types of labs performed by Duke BME students.

2.1 Lab 1: Introduction to Laboratory Measurements

I – Introduction

This lab provides a basic introduction of some of the equipment at each lab station, including the breadboard, power supply (BK Precision 1652 Triple Output DC Power Supply), handheld volt-ohm meter (VOM), and benchtop digital multimeter (DMM, Fluke 45 Dual Display Multimeter). This equipment is used to make a variety of voltage and resistance measurements used in designing different application circuits.

Students use these instruments to analyse the measurement accuracy which is generally defined as the measurement deviation from the "true" or ideal value as may be obtained through theoretical analysis or by some standard highly accurate measurement. They also analyze the difference between the absolute error as the difference between the observed value of a quantity and its true or known value and the relative error which is the absolute error as a percentage of the true value. Additionally, students note that these absolute and relative errors can be positive (meaning you measured a value larger than the true value) or negative (meaning you measured a value smaller than the true value). This lab also trains students to realize that a certain amount of random error occurs in all experiments and can be averaged out if a large number of measurements is taken.

This lab emphasizes some idea of an expected value when taking measurements thus accompanying each measurement with a relative error. Additionally, students notice that it is a good practice to record the value of the "least count-the smallest marked instrument division" which value represents the best-case accuracy for that particular measurement.

II – Objectives

- Learn to use the breadboard, power supply, volt-ohm meter, and digital multimeter at your lab station
- Measure voltages and resistors with your laboratory equipment
- Learn to record laboratory measurements
- Learn to measure the accuracy of your laboratory measurements
- Learn the lab report format

2.2 Lab 2: Ohm's Law and Power

I – Introduction

The first lab serves as an introduction to the lab equipment while making students familiar with voltage and resistance measurements. This second lab uses the same equipment to measure current and to test some more complex circuits.

Students get to realize that current can be measured two ways. The first, and perhaps easier method, is to use the ammeter function on the DMM. Students realise that this method is a little more complex than measuring voltage since it requires circuit reconstruction so as to allow current flow through the meter. Current flows *through* a circuit element though and for this reason the ammeter must actually be inserted into the circuit. Figure 1 shows how an ammeter might be used to measure the current through a resistor, R2. The other method for measuring current is more indirect and uses Ohm's Law.

Before building the circuit, the resistor is measured, and then once the circuit is built, the voltage across the circuit is measured and hence application of Ohm's Law yields the current (students are encouraged to maintain the sign convention). This second method is preferred when circuits become more complex.

Students additionally appreciate that power dissipated by any resistor is merely the voltage multiplied by the current and other equations can be generated by using Ohm's Law.

$P = VI$ (1)

But $V = IR$, so (2)

$P = V^2/R$ and (3)

$P = I^2R$. (4)

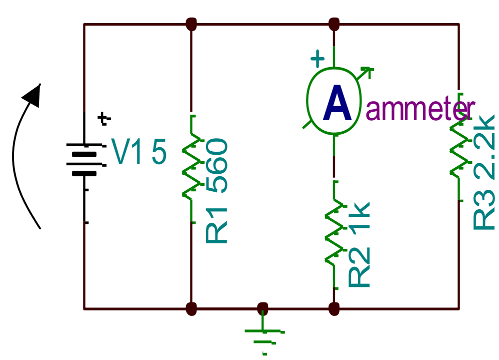


Figure 1: Example circuit showing how an ammeter is used to measure the current through R2

This lab also helps students to understand that all electrical devices have maximum ratings for their dissipated power. The maximum power for the standard resistors in this lab is given by the size of the resistor.

II– Objectives

- Learn to measure current using the digital multimeter
- Prove Ohm's Law
- Measure power indirectly
- Build a variable voltage divider circuit

2.3 Lab 3: The Wheatstone Bridge and Temperature Measurement

I – Introduction

The Wheatstone bridge circuit (Figure 2) is widely used in measurement systems. A change in the resistance of one of the arms of the bridge will change the output voltage (V_{out}). In a measurement system, one of the resistors is replaced by a transducer of some type, (R_T). The resistance of the transducer changes in response to a change in another physical parameter. Thus in the Wheatstone bridge measurement circuit, changes in a measurable physical quantity change the output voltage.

An equation for V_{out} can be found by applying Thevenin's theorem to the circuit of figure 2. First the circuit is re-drawn as in figure 3. The Thevenin voltages ($V_{TH1,2}$) and resistances ($R_{TH1,2}$) are then easily found (Figure 4).

$$R_{TH1} = R_1 || R_2, \quad V_{TH1} = V_{in} * R_2/(R_1 + R_2) \qquad (1)$$

$$R_{TH2} = R_3 || R_T, \quad V_{TH2} = V_{in} * R_T/(R_3 + R_T) \qquad (2)$$

The output voltage can then be defined as $V_{TH1} - V_{TH2}$ (since no current is flowing through R_{TH1} or R_{TH2}).

$$V_{out} = V_{in} * (R_2/(R_1 + R_2) - R_T/(R_3 + R_T)) \qquad (3)$$

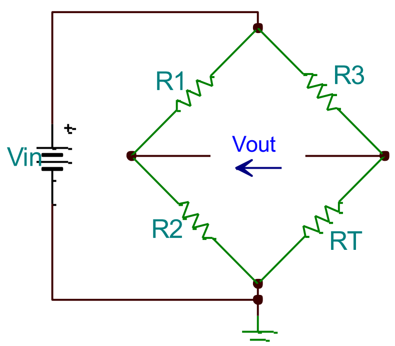


Figure 2: The Wheatstone bridge circuit

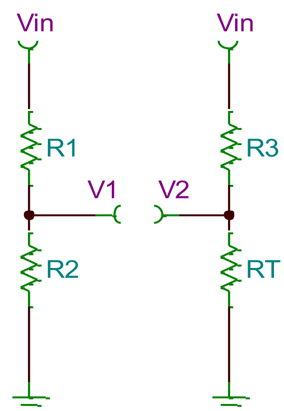


Figure 3: The Modified bridge circuit

The Wheatstone bridge can be balanced if $(R_1/R_2) = (R_3/R_T)$. In this case, the output voltage is zero.

In order to "balance" the bridge in a measurement system, R_2 is replaced by a potentiometer. The potentiometer resistance is varied until the output voltage is 0 V. The resistances of R_1, R_2, and R_3 are assumed to remain constant and the output voltage moves from 0 V only when the physical quantity that modulates RT changes from its value at balancing.[9]

In this lab, students use a thermistor with a small semiconductor as a transducer that

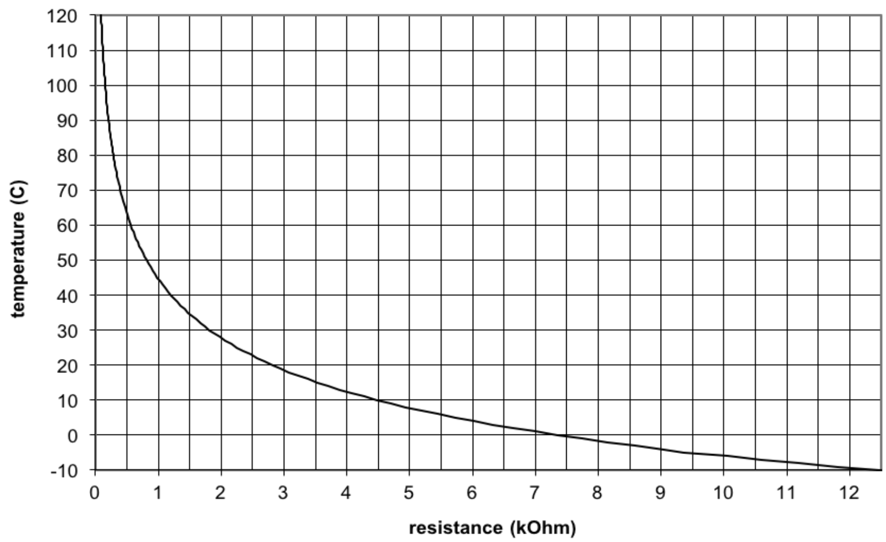


Figure 4: Temperature vs. resistance for 44033 thermistor

changes with temperature. The thermistors used in this lab have a negative temperature coefficient (NTC), meaning as the temperature rises the resistance decreases. The relationship between temperature and resistance may be seen in figure 4. The slope of the curve is called the sensitivity of the thermistor and is a measure of how a change in input (temperature) affects the output (resistance).

The students also realise that the relationship between temperature and resistance is not a simple equation hence no simple equation relating the entire range of temperature and output voltage can ever exist. However, over a small range, the relationship may be assumed to be approximately linear.

II – Objectives

- Build and balance a Wheatstone bridge circuit

- Calibrate a thermistor/bridge circuit with a bath at a known temperature
- Measure unknown temperatures with a calibrated circuit

2.4 Lab 4: Capacitors, Inductors, and the Oscilloscope

I – Introduction

This lab introduces the use of AC voltages where signals produced by circuits built with capacitors and inductors vary with time and thus can best be measured with an oscilloscope. This lab trains students on how to measure time varying or AC signals and introduces them to new lab tools, namely the function generator and oscilloscope. Additionally, in order to build circuits with more sophisticated signal-shaping capabilities, this lab introduces students to two new circuit components - the capacitor and the inductor.

Students appreciate that a sinusoidal AC signal may be uniquely described by four values - amplitude, frequency, phase and DC offset which values can be controlled by the function generator but one should never trust the numbers on this generator. However, students get to appreciate that the oscilloscope confirms all signals coming from the function generator and compares two AC signals in order to measure the difference in phase between them.

II – Objectives

- Learn to use the oscilloscope and function generator
- Measure capacitance and inductance with an LCR meter

- Learn how to measure the amplitude and phase of an AC signal

2.5 Lab 5: Input and Output Impedance

I – Introduction

Lab 5 trains students to realise the importance of "phasor" convention used to simplify calculations in alternating current (AC) circuits. In the phasor approach, time domain voltage and currents are transformed into frequency domain quantities known as phasors. For example, if

$i(t) = I_{max} \cos(\omega t + \theta)$ Amps, then the phasor is

$$I = I_{max}\, e^{j\theta} \qquad [\text{Amps}] \qquad (1)$$

or

$$I = I_{max} \angle \theta \qquad [\text{Amps}] \qquad (2)$$

The transformation proceeds as follows:

Suppose some $i_1(t) = I_{max}\, e^{j(\omega t + \theta)}$, then $i(t) = \mathbf{Re}(i_1(t)) = I_{max} \cos(\omega t + \theta)$, where **Re** ≡ the real part of $i_1(t)$. Now for steady-state sinusoidal signals, the time dependence is known and only the amplitude and phase will vary. Therefore, we suppress the $e^{j\omega t}$ for simplicity and write $I = I_{max}\, e^{j\theta}$ as the phasor. The effective signal (which is the equivalent DC signal to this sinusoid that would dissipate the same power through a circuit element) is the Root Mean Square (RMS) value of this signal. For sinusoidal inputs, the RMS value is the amplitude divided by $\sqrt{2}$. So, for this signal ($i_1(t)$), the RMS value would be $I_{max}/\sqrt{2}$. RMS values are generally used in power circuitry analysis as a matter of convention, and under this convention, the phasor notation is then modified to be the RMS value and the phase ($I_{max}/\sqrt{2}\angle\ \theta$). (Students are also charged with being aware that the formulae $I_{RMS} = I_{max}/\sqrt{2}$ or $V_{RMS} = V_{max}/\sqrt{2}$ only work for simple sinusoidal waveforms since computing RMS values for other AC waveforms is more complex.[10]

Additionally, if $v(t) = V_{max} \sin(\omega t + \theta)$, we observe that $v(t) = V_{max} \cos(\omega t - \Pi/2+\theta)$ and we define a complex voltage $v_1(t) = V_{max}\, e^{j(\omega t - \Pi/2+\theta)}$ Volts, so that the phasor **V** of $v(t)$ is

$$\mathbf{V} = V_{max}\, e^{j(-\Pi/2+\theta)} \text{ Volts} \qquad (3)$$

Students also realize the use of impedances when using phasor notation to solve circuits with sinusoidal signals, where the impedance of a resistor = R and is real, the impedance of a capacitor = $1/j\omega C$ and is imaginary, and the impedance of an inductor = $j\omega L$ and is imaginary. Thus the impedance, Z, may have a real part, R, and an imaginary part, the reactance X;

$$Z = R + jX \qquad (4)$$

This lab also helps students to analyze circuits as networks with inputs and outputs. A network has an input port and an output port and performs some functions (amplification, filtering, etc.) on an applied voltage or current signal. This serves as a way of characterizing a network through describing its input and output impedances. A key concept is that when two networks are connected together, their respective impedances will affect the output of the circuit.

II – Objectives

- Measure the impedance of capacitors and inductors
- Measure the input and output impedance of a complex circuit

2.6 Lab 6: Passive Filters

I – Introduction

This lab trains students to appreciate that filters alter an input signal $V_{in}(\omega)$ by some function of frequency, $T(\omega)$, such that the output $V_{out}(\omega) = T(\omega) * V_{in}(\omega)$. A schematic representation of a filter is shown in figure 5. The transfer function, $T(\omega)$, of the filter is defined by the following equation:

$$T(\omega) = V_{out}(\omega) / V_{in}(\omega) \quad (1)$$

The general case of a first-order filter is illustrated in figure 6 where Kirchoff's laws can be applied to obtain

$$V_{in} = I (Z_1 + Z_2) \quad (2)$$

$$V_{out} = I Z_2 = V_{in} Z_2 / (Z_1 + Z_2) \quad (3)$$

Therefore the transfer function is given by

$$T(\omega) = Z_2 / (Z_1 + Z_2) \quad (4)$$

An RC high pass filter is shown in figure 7, where $V_{in} = V_{in} \sin(\omega t)$, $Z_1 = 1 / j\omega C$, and $Z_2 = R$. This lab farther on demostarates the open circuit behaviour of a capacitor at low

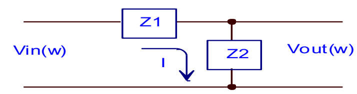


Figure 5: General first-order filter

frequencies and a short circuit behaviour at high frequencies, thus passing high frequencies and attenuating low frequencies. This hypothesis is verified by solving for the transfer function

$$T(\omega) = R / (R + 1/j\omega C) = 1 / (1 + 1/j\omega RC) \quad (5)$$

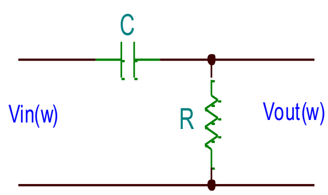


Figure 6: RC high pass filter

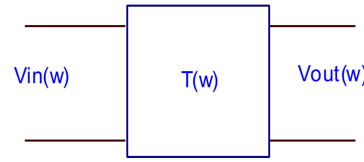


Figure 7: Transfer function

The fact that the transfer function is complex indicates that the output differs in phase from an AC input resulting in a transfer function magnitude given by

$$|T(\omega)| = 1 / \sqrt{(1 + 1/\omega^2R^2C^2)} \quad (6)$$

and a phase shift given by

$$\angle T(\omega) = - \text{arc tan}(-1/\omega RC) \quad (7)$$

This lab emphsizes the cut-off frequency, ω_c, which is defined to be the frequency at which the amplitude response of the system is $1/\sqrt{2}$ of maximum, or -3 dB. For this high pass filter $\omega_c = 1/RC$. Additionally, the students illustrate the frequency response of this high pass filter is in Bode plots of the voltage gain (in dB) and phase shift versus log ω where frequencies much higher than the cut-off frequency, make the current gain to approach unity, or 0 dB while the current phase to approach 0°. Below the cut-off frequency, the gain of the circuit has slope 20 dB/decade. (A decade of frequency spans from a particular frequency to ten times that frequency.) At frequencies much lower than the cut-off frequency, the phase goes to 90°.[11]

Other filters may be designed by substituting inductors, resistors and capacitors for Z_1 and Z_2 in figure 7. A first-order filter includes only one capacitor or one inductor, and ω is raised only to the first power. Analysis similar to that done on the RC high pass filter can be performed to find equations for the magnitude and phase of the transfer function as a function of frequency. If a filter attenuates high frequency signals and passes frequencies less than the cut-off frequency, it is called a low pass filter.

Second- or higher-order passive filters may also be designed. A typical second-order filter is the RLC notch filter. As the name suggests, it is built with a resistor, capacitor and inductor and passes all frequencies except for those in a narrow range (the "notch") centered around the resonant frequency, ω_0. Resonance is defined for an ω when the circuit looks entirely resistive.

II – Objectives

- Design and analyze passive filters

- Build high and low pass first-order filters
- Build a second-order filter

2.7 Lab 7: Transient Responses

I – Introduction

A time constant is the amount of time required for an exponential decay (or rise) to drop by approximately 63.2% of its initial value (i.e. 1/e). For first-order circuits, the time constant, τ, is *RC* for RC series circuits, or *L*/*R* for RL series circuits. An approximate measure of this value can be easily obtained from an oscilloscope display. Use a square wave input signal. Adjust the amplitude of the output signal so it fills eight vertical divisions on the scope. The time constant is then the amount of time for the amplitude to drop five divisions (see Figure 8). Use of Horizontal and Vertical Position knobs will help with positioning.[12]

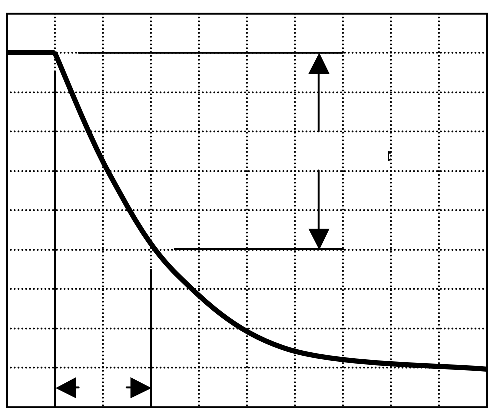


Figure 8: Approximate time constant of an exponentially

The oscilloscope cursors may also be used (in conjunction with the divisions) in a case where the amplitude of the input signal cannot be changed. Press the CURSOR button to bring up the cursor menu. Place one Voltage cursor at the peak of the signal just when it begins to drop. Then use the other to find the point where the voltage has fallen 63.2% (use a calculator to find this value) by reading ΔV on the scope. The time constant is then Δt between these points.

Although part of this lab is concerned with first-order systems (such as RC or RL circuits), the response of an RLC circuit—a second-order system—will also be analyzed. To gain a full understanding of the additional parameters associated with RLC circuits, it is perhaps best to start with the governing equations for any linear second-order system (i.e. electrical systems, mechanical systems, etc):

$$a_2 \frac{d^2x(t)}{dt^2} + a_1 \frac{dx(t)}{dt} + a_0 x(t) = b_0 f(t) \qquad (1)$$

$$\frac{1}{\omega_n^2} \frac{d^2x(t)}{dt^2} + \frac{2\zeta}{\omega_n} \frac{dx(t)}{dt} + x(t) = K_S f(t) \qquad (2)$$

The function x(t) is a general, time-varying function that can be used to model any time-varying parameter measured in the system (e.g. voltage or current for electrical purposes or displacement for mechanical applications). From the coefficients in equation (1), the following constants can be determined which hold true for all linear, second-order systems:

$\omega_n = \sqrt{a_0 / a_2}$, resonant frequency in radians/second (3)

$\zeta = (a_1 / 2)\sqrt{1/a_0 a_2}$, damping ratio (4)

$K_S = b_0 / a_0$, static sensitivity (5)

For the purposes of this lab, we are concerned with the following constants and parameters which pertain specifically to series RLC circuits (NOTE: the following parameters were derived by putting the governing, second-order differential equation of a series RLC circuit into the form given in equation (1) and using the governing relationships listed in equations (3-5) . The resonant frequency is the same for both a series and parallel RLC circuit, but the damping ratio is different. You should always derive the governing differential equations to evalute these parameters.):

$\omega_n = \dfrac{1}{\sqrt{LC}}$, resonant frequency in radians/second (6)

$\zeta = RC\dfrac{\omega_n}{2} = \dfrac{R}{2}\sqrt{\dfrac{C}{L}}$, damping ratio (7)

$Q = \dfrac{1}{2\zeta}$, quality factor (8)

$B = \dfrac{\omega_n}{Q} = \omega_n 2\zeta$, bandwidth in radians/second (9)

Three different types of responses from an RLC circuit are possible depending on the relationship between *R*, *L*, and *C* and can be characterized by a system's damping ratio:

ζ < 1, underdamped or oscillatory case (10)

ζ = 1, critically damped case (11)

$\zeta > 1$, overdamped case (12)

The frequency of the damped oscillation, also known as the damped natural frequency, is given by the equation:

$$\omega_d = \omega_n \sqrt{1-\zeta^2} \quad (13)$$

A filter may also act as a differentiator or integrator. Ideally, such a filter would have a ±90° phase shift. This is rather difficult to achieve with a simple RC or RL circuit and, for our purposes, a phase shift of about ±85° will be sufficient.[13]

II – Objectives

- Measure time constant for first-order circuits
- Measure the resonant and natural frequencies of an RLC circuit
- Explore the behavior of the LC resonating circuit

2.8 Lab 8: Transformers and Diodes

I – Introduction

The diode is a passive non-linear semiconductor device with many uses in all areas of electrical engineering and electronics. This lab concentrates on merely a few of its uses - clipping, clamping, and rectifying.

In simplest terms, the diode permits the easy flow of current through its two terminals

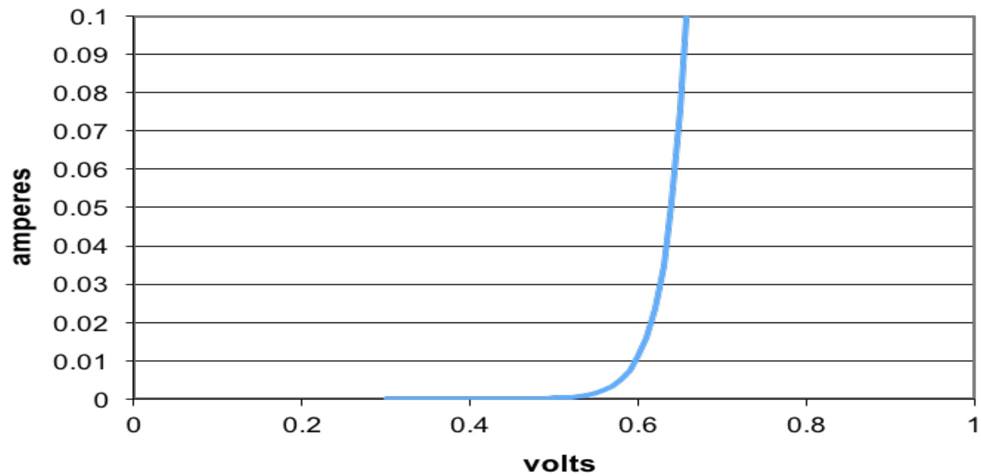


Figure 9: Forward V-I characteristic of a typical silicon diode

in one direction (from anode to cathode), but blocks current in the opposite direction. This behavior is most easily seen graphically. Figure 9 shows a typical voltage-current (or V-I) characteristic for a certain diode. This diode only passes current when the voltage across the diode is greater than 0.55 V. Therefore this lab trains students to first decide if and when (for AC problems) more than 0.55 V drops across such a diode when analyzing circuits. When the diode is "on" it can be modeled in the circuit as a small voltage source with magnitude equal to the threshold voltage.

This lab additionally explains how a transformer is a passive device that consists of two sets of insulated coils ("windings") each wrapped around a magnet. The transformer uses a magnetic core and an applied current in the input winding (the primary) to induce a current in the output winding (the secondary). By varying the number of wire loops in each winding, output voltage and current can be adjusted, though overall power remains the same (minus induction losses). The "winding ratio" defines this relationship, and with the input at V_S, is defined as:

$r = I_p/I_s = V_s/V_p = N_s/N_p$ (Equation 1)

where: r is the "winding ratio" or "turn ratio"

I is the current in each coil

N is the # of coils in the primary or secondary windings

Students evidently notice from the winding ratio equation above that a transformer can be a "step-down" or a "step-up" type depending on the windings. Transformers are used extensively in power transmission and electromechanical devices such as motors.[14,12]

In this lab, students first experiment with some diode circuits, and then build a half-wave rectifier. A rectifier is part of a circuit to convert an AC source into a DC source. For example, many consumer electronics devices draw 50/60 Hz AC power from a wall socket, but the device uses DC voltage for power. The AC voltage is first rectified and then filtered to remove the AC component. There is always still some AC ripple in all AC/DC converter circuits, but in well-constructed converters, it will have very low magnitude. The students finally measure this ripple voltage during this lab.

II – Objectives

- Build diode clamping and clipping circuits
- Wrap wire on a core to make a transformer

- Convert AC voltage to DC voltage

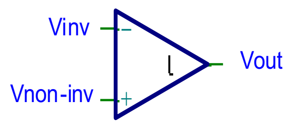


Figure 10: Schematic of ideal op-amp

2.9 Lab 9: The Operational Amplifier

I – Introduction

Operational amplifiers find a variety of applications in biomedical instrumentation. These versatile devices are used in wave shaping, filtering and amplifying input signals. Operational amplifiers are also capable of performing the mathematical operations of summation, subtraction, integration, and differentiation, and in combination can find real-time solutions to differential equations.

Ideal operational amplifiers exhibit infinite input impedance, infinite bandwidth, infinite open-loop voltage gain, and zero output impedance. During this lab, students appreciate a fundamental principle that the voltage difference between the two input terminals for thess amplifiers is always zero.[15,13] That is,

$$V_{inv} - V_{non\text{-}inv} = 0 \qquad (1)$$

Also,

$$I_{inv} + I_{non\text{-}inv} = 0 \qquad (2)$$

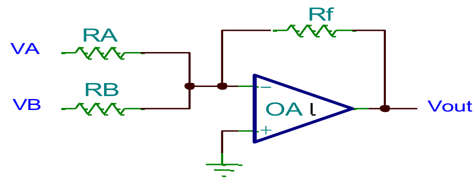


Figure 11: Schematic of the summer

because the input impedance is infinite.

Students appreciate that if signals are applied to the inverting input (labeled "–") the output voltage will be inverted from that of the input. If, however, signals are applied to the non-inverting input (labeled "+"), then the overall gain of the amplifier will be positive. If signals are applied to both inputs, a difference between the signals will appear at the output. This difference is very dependent on the values and configuration of external components.

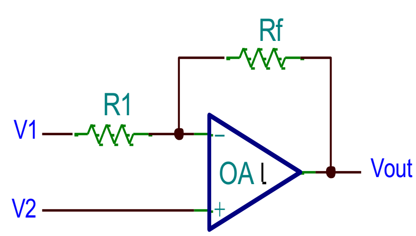


Figure 12: Schematic of generic differential amplifier

The use of the operational amplifier as a differential amplifier is illustrated in figure below. This configuration, like most op-amp circuits, uses *negative feedback* (the output is connected to the inverting input). Assuming ideal behavior, $V_{inv} = V_{non\text{-}inv} = V_2$. Using Kirchoff's laws the following expressions are obtained for the currents

$$I_1 = (V_1 - V_{inv}) / R_1 = (V_1 - V_2) / R_1 \quad (3)$$

$$I_f = (V_{out} - V_{inv}) / R_f = (V_{out} - V_2) / R_f \quad (4)$$

Since the input impedance of an ideal operational amplifier is infinite, $I_1 = -I_f$, and

$$V_{out} = (1 + R_f/R_1)\, V_2 - (R_f/R_1)\, V_1 \quad (5)$$

Students also note that V_1 and V_2 may be time-varying signals. If V_1 is grounded, the circuit in figure 11 will be called non-inverting amplifier. Alternatively, if V_2 is grounded, this circuit will be called an inverting amplifier.

The circuit shown in figure 12, is a standard application of the operational amplifier as signal summer. Assuming ideal behavior, $V_{inv} = V_{non\text{-}inv} = 0$. Applying Kirchoff's laws, the following expressions are obtained

$$V_A - I_A R_A = V_{inv} = 0 \quad (6)$$

$$V_B - I_B R_B = V_{inv} = 0 \quad (7)$$

$$V_{out} = V_{inv} + I_f R_f = I_f R_f \quad (8)$$

Since the input impedance of an ideal operational amplifier is infinite, $I_A + I_B = -I_f$. Therefore, the output voltage of the summer is

$$V_{out} = -(R_f / R_A)\, V_A - (R_f / R_B)\, V_B \quad (9)$$

The use of the operational amplifier as an integrator is illustrated in figure 13. Ideally, $Z_f = 1 / j\omega C_f$ and $Z_1 = R_1$. However, real operational amplifiers often exhibit a small "offset" current. That is, the output may not be exactly zero when $V_1=0$. If this condition exists, then both the DC offset voltage and the AC input signal are integrated since[16]

$$V_{out} = -1/(R_1C_f) \int V_1 \, dt \qquad (10)$$

Thus the output rises to near the positive voltage supply, V_{cc} and the portion of the signal above V_{cc} is clipped. To avoid this problem, a resistor is placed in parallel with the feedback capacitor. This provides a path for the DC current and only the AC input will be integrated.

II – Objectives

- Build and test inverting and non-inverting amplifiers
- Build and test an integrator

2.10 Lab 10: Pulse Plethysmography

I - Introduction

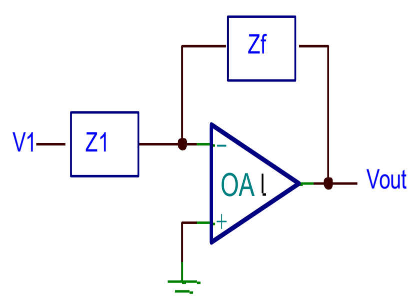


Figure 13: Schematic of op-amp integrator

Plethysmography is the measure of changes in volume. Pulse plethysmography measures the pulsatile volume changes of blood in the vascular system. The pulse plethysmograph is the primary building block of pulse oximetry, one of the standards of care in many areas of clinical medicine.

Blood is constantly pulsing beneath a person's skin. After the heart's ventricle contracts, systematic arterial blood pressure rises to systole. Between beats, the pressure of the system decreases to a resting value, diastole. This pulsatile change in blood pressure results in a volume change in the somewhat elastic arteries and arterioles throughout the body.

A pulse plethysmograph measures volume changes using light transmittance. The light source is typically a light-emitting diode, or LED. The light entering the tissue is referred to as Incident Light, I_0. The transmitted or received light, I, is equal to the I_0 minus the light absorbed by the tissue. (Scattering effects are ignored here.) The received light signal, I, will vary with time with the local volume change at the site of plethysmography.

The figure below shows a pulse Plethysmograph signal indicating the inter-relation between light absorption with time.

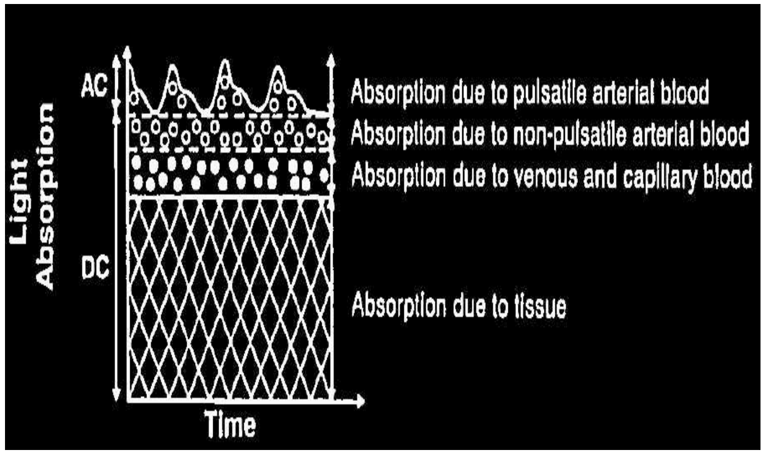


Figure 14: Pulse plethysmography

Application

During this lab, students build the following circuit and ensure using clean fingers onto which they apply a probe. The subject under test breathes quietly and keeps still. After a few seconds, this subject realizes a pulse plethysmograph waveform display onto the oscilloscope. If not, and the signal is well below 5 V, the student may need to turn the LED drive level up. A cold finger could also be a problem and one may need to warm it up. If the student is still unable to see his/her signal, he/she may need to ensure that the LEDs and photodiode windows are aligned.

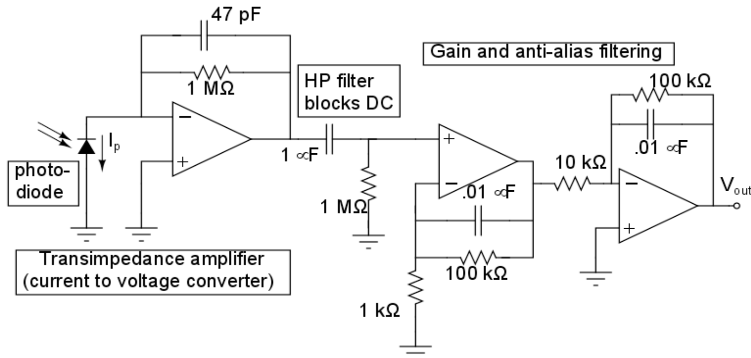


Figure 15: Transimpedence circuit

II – Objectives

- Effect of a trans-impedance amplifier
- Effect of a photo-diode
- Plethysmography

Conclusion:

The above labs are intended to help students connect the theoretical class lectures with the practical exercises as they match together.

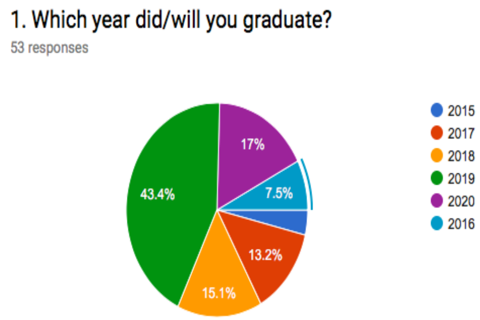
CHAPTER THREE - DATA ANALYSIS AND FINDINGS:

3.0 INTRODUCTION:

In this chapter the results of the data analysis are presented. The data were collected and then processed in response to the problems posed in chapter one of this dissertation. Two fundamental goals drove the collection of this data and the subsequent data analysis. Those goals were to develop a base of knowledge about the current trend of electrical circuits classes as it is perceived and utilized relative to the previous students who have already taken them at Makerere University, and to determine if current perception and utilization are consistent with the basic goals or principles of the BME program. These objectives were accomplished. The findings presented in this chapter demonstrate the potential for merging theory and practice.

3.1 Response rate

A random survey of questionnaires was initially sent to former students and current junior and senior students who have already completed the electrical circuits course at Makerere. As shown in the figure below, 53 surveys which were returned included 6 students who had graduated in 2016 (first graduation cohort), 7 students who had graduated in 2017, 8 students who hope to graduate in 2018, 23 students who hope to graduate in 2019 (current seniors) and 9 students who hope to graduate in 2020 (current juniors).

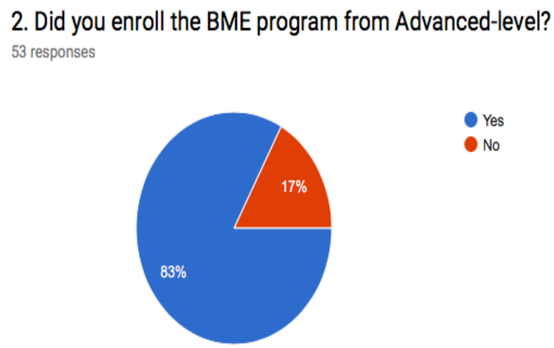


3.1.1 Response rate analysis

The response was highest from the current senior and junior students because of their availability as compared to other cohorts who had already completed their BME program. Some students never returned the questionnaires and some had no online application for them to receive and reply the questionnaires. The percentages also greatly vary because of the different class enrollments where different years had different number of students.

3.2 Program enrollment mode

The figure below represents the student percentages that enrolled from ether advanced level or other entry levels. In Uganda, most students enroll the undergraduate programs through advanced level although a few of them enter through other levels. 17% of the respondents did not enroll in the BME program from Advanced level as compared to



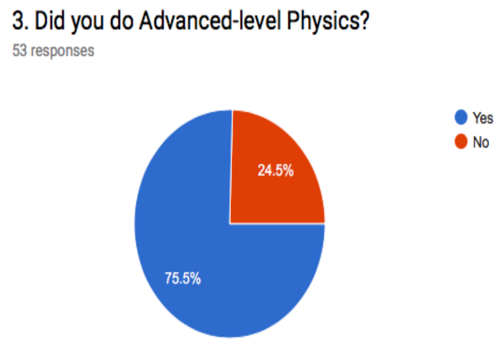
the remaining 83%.

3.2.1 Program enrollment mode analysis

The above results were expected since most of the students enroll in undergraduate programs from advanced level. This enrollment also suggests that some of these 17% students could have either taken some time before joining University or could have joined with different entry selection criteria. Such differences could have impacted their class performance and thus yielding to lower grades.

3.3 Advanced level Physics

Advanced level physics is one of the key requirements for joining any engineering program in Uganda. However, since BME is a wide program linking medicine with engineering principles, the curriculum allows students to join with other subjects like biology, chemistry and mathematics without having taken advanced physics. Research indicated that 24.5% never did advanced level physics as compared to 75.5% of the total respondents.

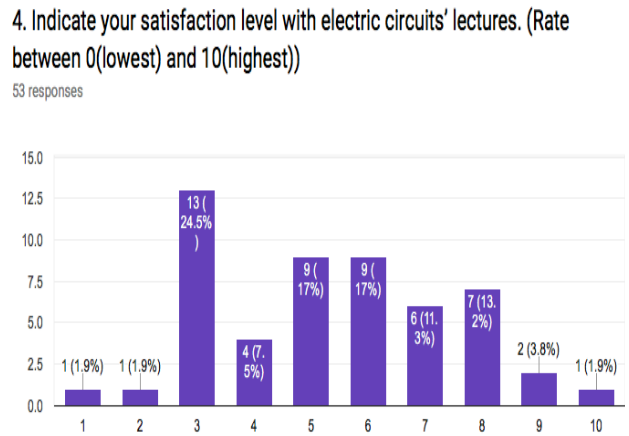


3.3.1 Advanced level physics analysis

The above data indicates a dilemma in competition between the BME and the other engineering students especially in regards to electrical circuits which is purely a physics subject. This dilemma also extends to some who did physics and obtained low grades because the BME admission committee could have neglected this low physics grade and considered high grades either from biology or chemistry. Both of these challenges culminate to low competition amongst such students and thus low scores after exams.

3.4 Satisfaction level from the electrical circuits lectures

The graph below indicates a satisfaction level analysis obtained from different responses towards the electrical circuits lectures taken. The vertical axis indicates the number of students whereas the horizontal scale indicates the satisfaction range.

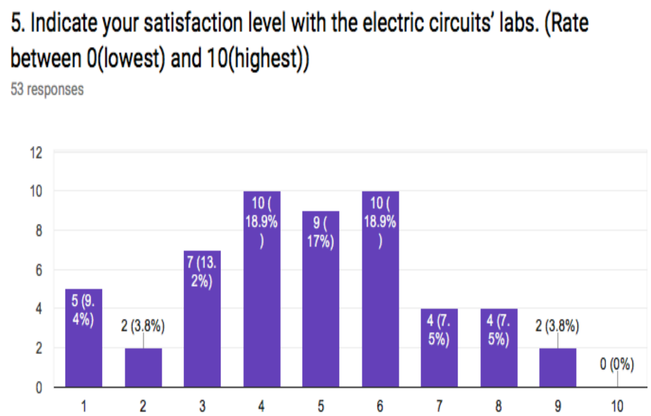


3.4.1 Analysis for the above Satisfaction level

This data indicates that the highest percentage (24.5%) of students were only 30% satisfied with the electric circuits lectures. This could be explained by some of the gaps discussed above like no physics background, other University entry modes, methods of teaching and exposure to different labs. The large class sizes could additionally explain this low satisfaction level where competition was never favorable. Classes were composed of a mixture of electrical, telecommunications, computer and BME students.

3.5 Satisfaction level from the electrical circuits labs

The graph below indicates a satisfaction level analysis obtained from different responses towards the electrical circuits labs taken.

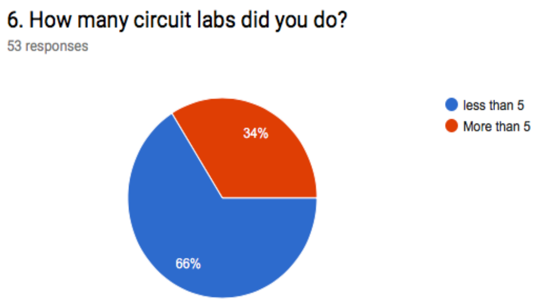


3.5.1 Analysis for the above Satisfaction level

The data indicates that more than 60% of the students reported less than 50% satisfaction level from the electric circuits lab. This was probably due to the large lab group numbers (like of 8–12 students) where most of them never fully participated in the lab exercises. This lack of participation could have affected the student morale thus lowering their grades since they could not connect the theory with the practicals carried out.

3.6 Number of electrical circuit labs

As mentioned earlier, the electrical circuits course had 4 programs (like Electrical, Telecommunication, Computer and BME students) taught at ago leading to large class numbers. Such numbers had to match the available lab resources causing large groups as indicated by the chart. The chart below indicates the number of labs done by different students with the majority having done less than 5 labs.

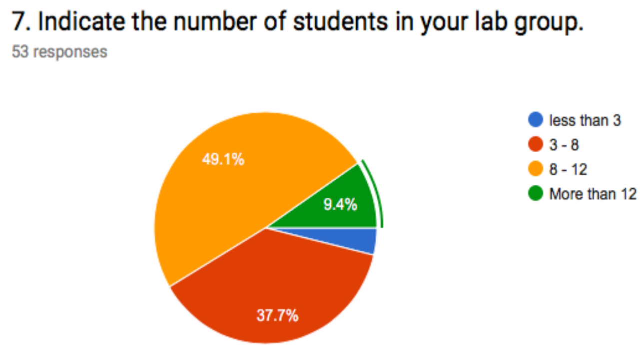


3.6.1 Analysis for the number of circuit labs

Given the large class numbers, probably the lab technicians get overwhelmed and fail to attend to every student's need. This challenge in return reflects onto the student's way of lab appreciation and limits the number of labs they do. Some students do not even care since these labs contribute to only 20% of their final grade making them concentrate on the final exam that yields to 60%.

3.7 Number of lab members

Large numbers of lab members always had to match the available lab resources causing large groups as indicated by the chart. The chart below indicates the number of lab members per group during the previous instrumentation classes.

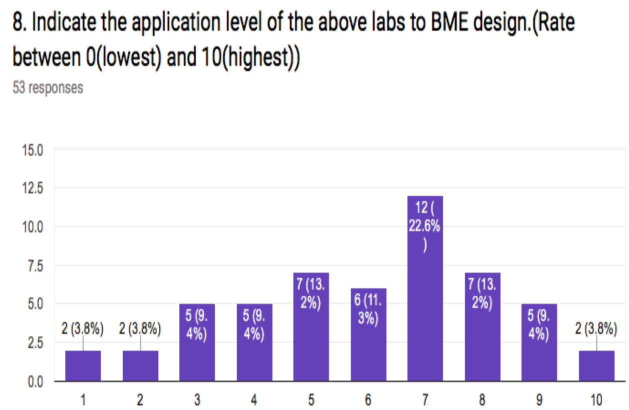


3.7.1 Analysis for the number of lab members

More than 50% of the students had 8 or more members in their group all sharing the same lab equipment. This data justifies the hypothetical suggestion of designing a BME lab which will help reduce the student lab numbers. Such large numbers can never help students obtain the best out of their lab activities since only a few of them can hold components while the rest just look on. This scenario later on results in low grades and poor concept understanding in line with the electrical circuits.

3.8 Application level for the labs during the BME design courses

Makerere University BME curriculum requires students to take 4 design courses during their third and fourth years. Such design courses try to embrace all modules covered by students during their four years and help students to realize their profession as engineers. The figure below indicates the application level of the already done labs to the BME design course.

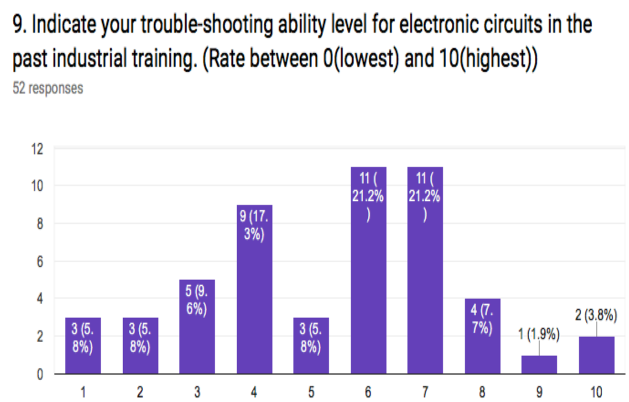


3.8.1 Analysis for the application level for the circuits labs

This analysis looks at the usability of the electric circuit principles during the design courses taken in third and fourth year. Although the above application of the circuits labs may not necessarily depend on the mastery of the course content, the content knowledge dictates the design interest. The graph indicates somehow an even distribution with 70% of these labs applied by most of the students. This could probably have been due to the type of design or the physicians' need. (Note – some of these designs are dictated by the physicians so that students help in improving them.) This additionally indicates a high relevance of the electronic circuits in the BME design courses.

3.9 Industrial training trouble-shooting ability

The curriculum tasks students to go for industrial training after their second and third years. This attachment helps students to familiarize themselves with the working environment and apply the theoretical principles to the practical challenges. The graph below reports student confidence in circuits during their industrial training.

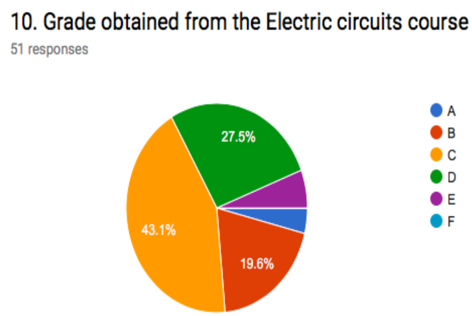


3.9.1 Analysis for the industrial training trouble-shooting ability

The graph above fairly indicates the data from the trouble-shooting ability with more than half the students able to apply less than 50% of the electrical circuits principles. Although this industrial training serves as an opportunity for improving hands-on skills, this opportunity provides better rewards when the theory and attached practicals are understood by the students.

3.10 Grades obtained

The figure below shows the different grades obtained by different students in the electrical circuits course.



3.10.1 Analysis for the grades obtained

The above grades confirm the existence of a problem as they indicate the majority of the BME students below C. This motivates a need for a solution to improve such scores and equip the students with better knowledge necessary for the BME program. The section below indicates several recommendations suggested by students in line with this course improvement.

3.11 Student Recommendations

The following are some of the recommendations obtained from students towards improving this Electrical circuits course.

- ✓ "Electric circuits course should include the aspect for medical equipment
- ✓ The course should be tailored more to BME
- ✓ More hands on laboratory sessions with less people to enable access to the bench work table and components

- ✓ Reduce the number of students per group for better appreciation of the labs -give examples during theory lectures to relate the content to biomedical engineering -labs done were few, we could not appreciate the theory well since we had not tried them practically -the unit also needs a BME lab for practicals, building prototypes and testing students' designs done in the biomedical engineering design modules -the number of instructors in the lab session should also be at least 2 depending on number of students doing the lab such that every group is covered
- ✓ We should have fewer members in the groups .And more time is needed in the labs
- ✓ Detailed explanation
- ✓ Less theory and more practicals
- ✓ There's great need of setting up a BME circuits lab to improve the course
- ✓ More practicals related to medical field are required. - Students require to be exposed to medical equipment before at least their first internship as part of the labs.
- ✓ There should be direct fusing of the lectures and the labs like every theory should have practical lectures offered before the student forgets the theoretical part
- ✓ Less individuals in the lab group and more practical time
- ✓ The course being a practical one, students should be exposed to more practical work then what the university is providing currently.
- ✓ The course outline must be provided so as to know what exactly is to be covered.

- ✓ The biomedical engineering department should be given special attention and services as it requires a lot of exposure an and expertise. This implies that students should be given their laboratory as well as defined instructors. -there is need for qualified lecturers who can guide the junior lecturers.
- ✓ The practicals should incorporate already existing and mostly used medical equipment so as to get conversant with the technologies
- ✓ Given that the combined class that is including Biomedical, Telecom and Electrical Engineering is excessively big, I would rather the Biomedical Engineering students be taught on their own while they are alone. This will enable better lecturer-student interaction and the students will thus benefit from the labs.
- ✓ If a learning schedule can be drafted and made available to all students of BME which is different from that of CEDAT. Actually even the practicals we had are very few that most of the aspects are not grasped during these practical sessions. its all about writing reports and getting marks but the real knowledge is not acquired. if these practical aspects can be strongly emphasized than just writing to pass. it would be the best way to teach.
- ✓ I believe the labs should be more of course specific. This is because i did labs for electromagnetics once and it was mainly wave guides application in the telecommunications field. Such does not give the BME students room to explore their

own field. Even more so the lab sessions are usually overcrowded with more than 8 people per bench

- ✓ A very practical approach would be very beneficial to the program; Having the components of discussion readily available during lecture time with simulations of their applications would go a long way in the betterment of the module.
- ✓ Implementation of the reviewed curriculum, construction of the BME LAB, Establishment BME department, Partnership with intern organizations and sensitizing them of their expected roles and duties in training the students.
- ✓ Make the course unit more practical
- ✓ More lecturers are needed
- ✓ We need to have enough hand on practice and exposure in BME related fields
- ✓ I did internship from Ministry Of Health, Health Infrastructure Division in 2017. There are a lot of redundant equipment that are disposed, which instead would be posted to the University for learning purpose by Biomedical Engineering students.
- ✓ It should be more practical and updated. We were taught outdated information. try to simplify the teaching methods for EC. It requires slow but sure teaching and should be very detailed. Though it's very essential for an engineer.
- ✓ more exposure of students to the electronic labs
- ✓ Let it be more hands on in regards to dealing with medical equipment.
- ✓ More practical lessons/labs

- ✓ We need more hands on experience because our course is practical.
- ✓ They should put much more effort and time on the practicals than theory
- ✓ The course unit is very essential in Biomedical Engineering however there presents need to relate it to Biomedical Engineering n have more of the practicals, they do make the theories easier
- ✓ We need better facilities pertaining electronics labs
- ✓ The infrastructure needs to be set up and instruments or equipment put in for the students to learn from, and more tutors need to be attached to the lab to allow for hands learning
- ✓ More emphasis should be put on practicals than on theory. A BME electronics lab should be set up and the number of students per group should be a minimum as possible (2-4) to enable each student have amble time for hands on training.
- ✓ More labs should be carried out in smaller groups in relation to medical equipment
- ✓ More electronics exposure sessions in the curriculum, more lab equipment, more application-based lab sessions
- ✓ More labs exposure is needed to perfect the theoretical knowledge.
- ✓ Problem based learning; get students involved and explaining everything basing on what is present in the country
- ✓ Labs should be construed for the biomedical department
- ✓ Reduce on the number of students per group in order to maximize participation

- ✓ I really love the way electronic circuit lectures were conducted and the contents therein. However, the knowledge we got would carry more sense when we have a concurrent hands-on lab practices.
- ✓ They should try to restructure BME curriculum
- ✓ We strongly need a lab of our own as biomedical engineering students to make our learning process very effective in the electric circuit course units
- ✓ Lecturers should encourage understanding rather than cramming and more labs!!
- ✓ we need more practicals and they should also let students do projects that require the application of what is studied in class
- ✓ Should be tailored for teaching BME, as well reduce the size of lab classes for better facilitator-student contact
- ✓ It's should be more student engaging in terms of practical exposure
- ✓ more labs with less students per station, studying electronic circuit labs with the application view from the beginning, more practical course.
- ✓ Practicals should be on individual basis.
- ✓ Improve technology used during training
- ✓ more exposure needed"

3.12 Conclusion

The charts and the above students' recommendations from this chapter strengthen the need for a frugal BME lab that would support the design classes and theoretical understanding towards the BME instrumentation class.

CHAPTER FOUR - CURRENT STATUS AND PROPOSED MUK BME LAB DESIGN

4.0 INTRODUCTION

This chapter discusses the current status and the researcher's proposed BME lab design. Additionally, this chapter highlights the human resource, the current lab space dimensions, the furniture and fittings, the training equipment, lab reagents and consumables.

4.1 Aims of the proposed BME lab

The proposed biomedical engineering lab will first of all aim at improving students' learning experiences and research projects, secondly this lab will aim at providing continuous professional training to clinicians regarding medical and laboratory equipment. This lab will also offer contracts for repair, maintenance and servicing of medical equipment to the university, external laboratories and medical facilities. This lab will greatly reduce the overall costs of equipment repair and service since there is currently no similar lab in Uganda. This lab will finally strengthen the BME mission pillars - innovation, service delivery and giving back to the community.

4.2 Detailed activities of the BME lab

4.2.1 Training

This BME lab will mainly focus on the following categories of students.

4.2.1.1 The undergraduate category

This category will be trained in order to introduce them to the BME practical skills, hands-on training experience and this training will act as a connection bridge between theory and practicals. This category will also be able to secure internship opportunities from various places that may seek support from this BME lab. The undergraduate medical students will also be among the other students that will directly benefit from this lab especially in learning how to use medical equipment.

4.2.1.2 The graduates

This category will involve BME masters and doctoral students carrying out innovative research. The lab will base its development on programs within the field of biomedical engineering including optical engineering, tissue engineering, biomechanics, rehabilitation and assistive technology, medical imaging, environmental engineering, clinical engineering, and embedded medical systems among others. This lab will provide a platform for these researchers to carry out their research in the most suitable environments and will also accommodate other researchers from the university and elsewhere who might need this lab.

4.2.1.3 Short Courses

There are quite a number of short courses that can be taken up in the field of biomedical engineering. These courses can be obtained from the different BME sections like bioinformatics, imaging, instrumentation and many others. The target group will be the in-service members who mainly need an improvement in their operation skills. This activity will involve short daily, weekly and monthly programs that will be conducted to enhance the performance of the participants.

4.2.2 Research, innovation and development

Research and innovation for social and economic development is becoming universally important due to the need for progressive development. This activity will involve the development of new ideas and other procedures for solving health related problems from both local and global sectors thus promoting the Makerere BME program. This lab activity will enhance the task of determining solutions for the most pressing health technological needs through research and ensure that ideas get transformed into breakthrough innovations that have the potential to improve people's lives. Secondly, this lab will support the postgraduate students whose specializations may be from different BME fields like biomechanics, rehabilitative and assistive technology, tissue engineering, bioinformatics and clinical engineering hence improving the research potential in the college. The lab will also support external researchers whose research is focused on improving the people's health.

4.2.3 Service delivery

Makerere University College of Health Sciences incurs high expenses in repair, maintenance and servicing of its medical and laboratory equipment due to the lack of internal employee service providers. This biomedical engineering lab with its qualified staff could save such high expenses by providing these services to the college. The college has a variety of medical equipment in different departments such as department of Pathology, Medical Microbiology, Molecular Biology and Physiology.

With the brand name of the university, the lab will also obtain both internal and external contracts that will be used to obtain funds within the college. This name will also provide the lab with a high chance of winning such contracts because Makerere University is known for producing excellent and competent personnel.

Some of the target facilities to be served by this lab include Mulago National Referral hospital, Uganda Virus Research Institute, Kampala international hospital, Kampala city council health facilities, and other public and private health facilities.

The lab will also focus on providing different required spare parts for various equipment as well as training medical and laboratory staff in acquiring certification in medical equipment calibration and standardization. The facility will also act as a local representative for different Biomedical equipment manufacturers both internationally and within the region.

4.3 Resource Mobilization

This BME lab will source its funding from activities such as training, equipment repair and maintenance. Other sources of funding looked at are levying research fees from scientists who will be using the lab for their projects. The lab will also focus on acquiring funding through applying for grants, donations, patents and endorsement funding. According to the university 10% of this fund will go to the college, 10% to the school of biomedical sciences and 5% to the university. This will be distributed after a total deduction of 30% taxation on any fund leaving the remainder for this BME lab.

All funding being raised by the workshops and the BME lab after total deduction of what goes to the university, college and school, will go to the physiology department to support biomedical engineering lab activities. Some on these activities will include outsourcing of consumables, facilitation of the workshop staff and support for the development of biomedical engineering students' projects.

4.4 BME lab requirements

This section fully describes some of the requirements needed for this lab to take effect and a few that are already available. Unfortunately, some of these available equipment partially operate while others cannot operate due to a need for key accessories.

4.4.1 Human resource

So far, the biomedical engineering team is made of more than six members comprising of a PhD holder in BME, two students completing their BME master's programs and more than five BME bachelor's graduates. In addition to the above, the lab might recruit one more electrical technician, a refrigeration technician and a biomedical technician to help support its activities.

4.4.2 Lab space

The biomedical engineering lab currently occupies a room sized space of about 7m by 3m in the physiology department which may increase with time given the lab requirements. The other additional room requirements include renovation and furnishing that can be worked on by the physiology department.

Figure 16: Current BME lab

4.4.3 Lab furniture and fittings

The current lab space has some furniture although not well suited for the lab design hence more workshop furniture for example lab benches, cupboards, stools, lights and power sockets adhering to the workshop requirements is needed. There is also need for more extension cables to support the many devices that are to be used since the workshop has only one extension cable.

4.4.4 Lab equipment

Although the BME program was given some electrical equipment and accessories through its Canadian partners to facilitate training, this equipment was not sufficient because it lacked some key accessories. Some of these tools and equipment are listed in the table below.

Table 3: List of equipment found in the biomedical engineering lab that were donated by its partners in Canada

EQUIPMENT NAME	SERIAL NUMBER	QUANTITY
Digital hand held meters	UT 33series	10
Commercial electric digital multimeter big	81510801003 1	5
Functional Generators (tektronix)	E200664	2
Signal generators		06
Binocular microscope	102155	1
Oxygen concentrator		1
Oxygen meters	026.05615	13
ECG machine		1
Tool kit		1
Automatic voltage regulators	JSGS201203 A000363 JGSS201203 B001490 JSGS201203	3

	A000782	
Defibrillator	D97D11744	1
Wire strippers		3
Soldering gun	5601	1
Voltage tester		1
DC adapter	6872A005	1

4.4.5 Reagents and consumables

Duke University provided the following consumables that have greatly facilitated labs for the electronics circuits class that will be commented about in chapter five. Although listed as consumables, these components can be used multiple times.

Table 4: List of consumables found in the biomedical engineering lab that were donated by Duke University

ITEM	NUMBER OF PIECES
Resistors	130
Capacitors	35
Inductors	30
AGW (50 ft wire)	5
1N914 diode	5
LM353 op-amp	10
LF353 op-amp	10
Potentiometer	10
Fingertip pulse probe	10
Breadboards	11
Red LED lights	10

Green LED lights	10
Photodiode	10
Thermistor (model 44033)	10
Bulb thermometer (GT 737000)	10
Transformer cores	10

4.5 Conclusion

This chapter indicates that although there's an urgent need for a frugal lab to assist in the BME instrumentation class, Makerere BME program already has a few items to utilize in setting up such a lab.

CHAPTER FIVE –BME INSTRUMENTATION COURSE PILOTED AT MAKERERE

5.0 INTRODUCTION

This chapter is intended to present the progress of the first offering of the new BME instrumentation course taught at Makerere University that was designed this past summer following the Duke course model. The course is enrolled by a total of 21 men and 12 women. Out of these 33 students, 8 students had not previously taken an advanced physics subject and 5 students just wished to improve their previous grades. Additionally, this course has 10 lab experiments for the students to appreciate electrical components design and instrumentation. The labs are currently being offered during a 3-hour window each week in the Makerere ECE laboratory facilities.

5.1 Comments on the Assessment

This section discusses the midterm performance of candidates both in theory and lab experiments. Theoretical assessment involved homework and midterm exam while lab assessment involved the three lab experiments carried out so far.

5.1.1 Component 1: Midterm Exam

The midterm exam had five questions each carrying 10 marks as indicated below. This exam comprised of only calculations covered from the previous topics as well as some specific principles obtained from the lab activities. There was a good range of questions in terms of difficulty, and such questions showed good discrimination with reference to what had been taught.

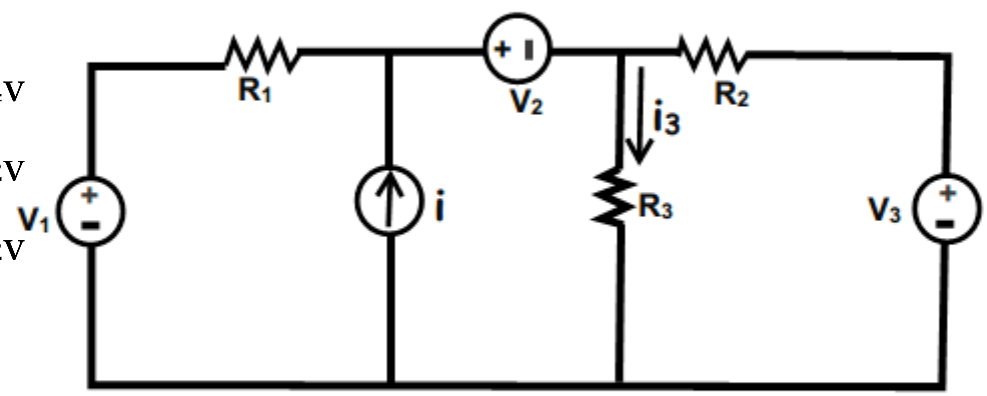
Question 1: Clearly apply either Branch Current Method or the Mesh Current Method to find i_3, the current through resistor R_3, by finding and solving a system of simultaneous equations using only the minimum number of equations necessary. "Clearly" means: Explicitly show all steps for the process of applying the Branch/Mesh Current Method, and provide all necessary voltages and/or current labels on the circuit.

$V_1 = 24V$

$V_2 = 12V$

$V_3 = 32V$

$i = 2A$



Question 2: Determine the requested unknown quantities in the circuit below.

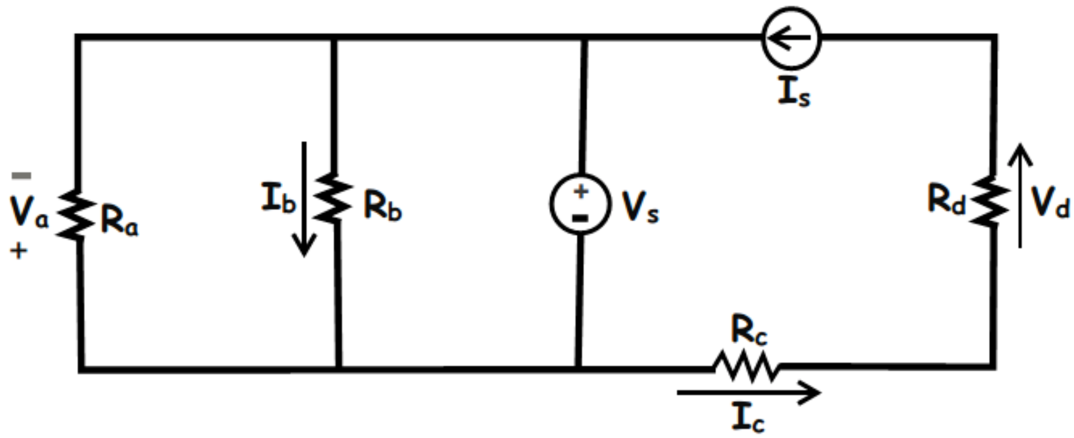
a) The voltage across the resistor R_a, denoted by V_a in the diagram.

b) The current through resistor R_b, denoted by I_b in the diagram

c) The current through resistor R_c, denoted by I_c

d) The voltage across resistor R_d, denoted by V_d.

e) The total power delivered by both sources



Given:

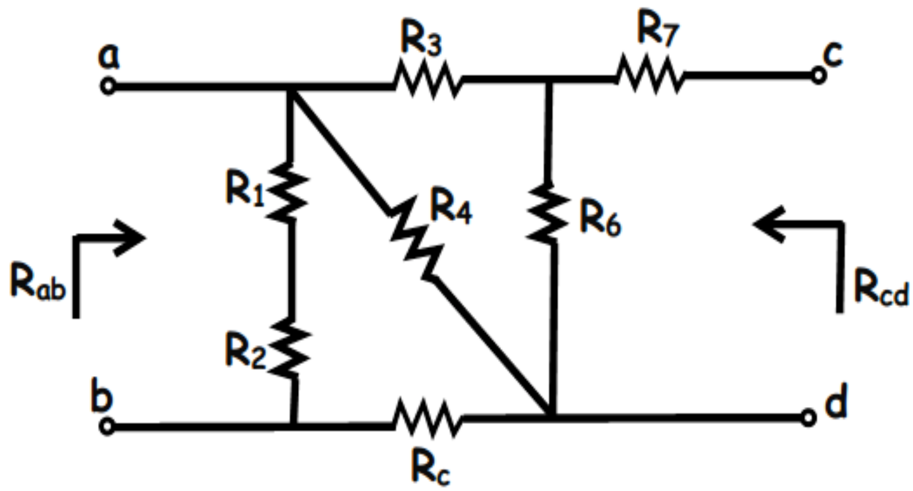
Question 3: For the resistor network below; provide

a) The equivalent resistance between terminals a and b; R_{ab}.

b) The equivalent resistance between terminals c and d, R_{cd}.

- Given;

$R_1 = 5\Omega$, $R_2 = 3\Omega$, $R_3 = 5\Omega$, $R_4 = 3\Omega$, $R_5 = 5\Omega$, $R_6 = 4\Omega$,

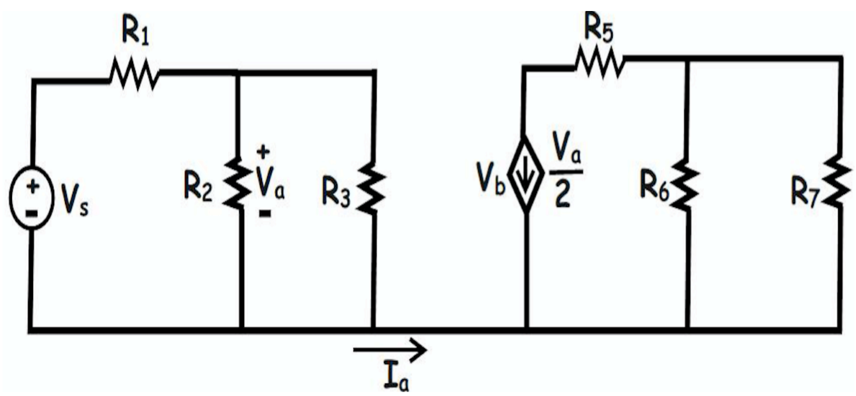


Question 4: Determine the requested unknown quantities in the circuit below,

a) The current denoted by I_a in the circuit below

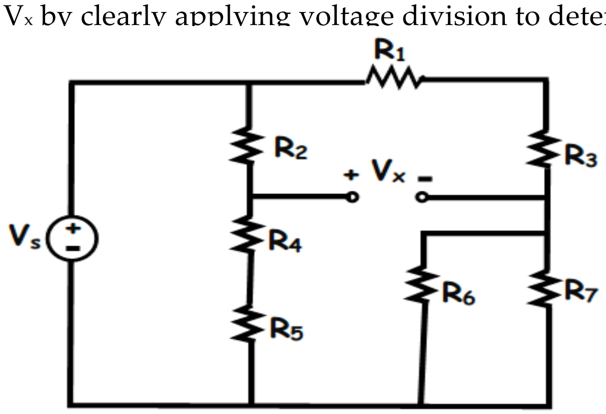
b) The voltage drop across the dependent current source denoted by V_b in the circuit diagram. Given;

V_s = 20V, R_1 = 8Ω, R_2 = 20Ω, R_3 = 80Ω, R_5 = 15Ω, R_6 = 50Ω, R_7 = 50Ω



Question 5: Find V_x by clearly applying voltage division to determine the node voltage necessary to find

Given;



-

Given, V_s = 20V, R_1 = 10Ω, R_2 = 4Ω, R_3 = 2Ω , R_4 = 9Ω,

R_5 = 5Ω, R_6 = 20Ω, R_7 = 5Ω

Figure 17: Candidates during their midterm exam

5.1.2 Component 2: Electrical circuits labs

Candidates managed to do three electrical circuits lab activities each weighing 20 marks. The weight for each criterion assessed as part of the lab assignment is given in the table 5 below. Most of the lab groups comprised of 4 candidates and this selection was dictated by the students themselves. This selection method was chosen so as to allow comfortable discussion and learning amongst these candidates. Figures 18 and 19 indicate some of the lab groups carrying out the calibration experiment.

Table 5: Showing the criterion used while marking labs

Criteria	Mark allocation
Aim(s)	1
Applying knowledge and understanding of circuits	4
Selecting circuit components and equipment	2
Procedure	1
Processing and presenting data/information	4
Analyzing data/information	2
Conclusion(s)	1

Evaluation	3
Presentation	2

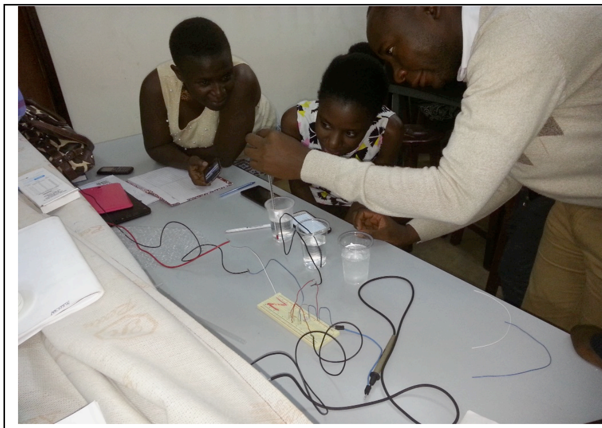


Figure 18: One of the lab groups during the calibration lab

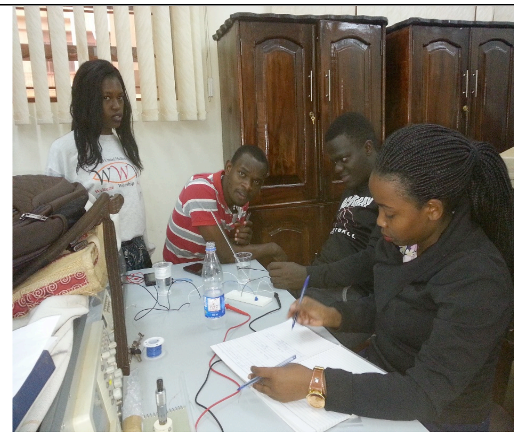


Figure 19: Another lab group during the calibration lab One of the lab groups during the calibration lab

This second assessment component also performed as anticipated. The average mark for this component rose with the labs done and a good number of candidates managed to achieve full marks with a few candidates scoring slightly lower marks.

	
Figure 20: How the iced water was kept during the calibration lab	**Figure 21: How water was boiled for this calibration lab**

5.2 Comments on candidate performance

5.2.1 Component 1: Midterm exam

Table 6 below indicates the analysis from the midterm exam. Numbers 2, 3 and 4 were the best done questions as compared to number 1 which was worst done. This was probably due to the high practical exposure to different resistors during lab 1 and 2 while noting their connection effects with the DC power supply. Numbers 1 and 5 were poorly performed mainly due to careless mistakes and wrong assumptions by some candidates. Additionally, number 3 had the highest mean mark and the lowest standard deviation which indicated that almost all candidates scored close to this mean mark of 8.3. However, a number of candidates achieved above 8 marks per question although no candidate achieved all the 50 marks. This performance verifies the hypothesis for a need to design, implement, and evaluation of a Novel BME instrumentation course. Group presentations as shown in the figure 22 below facilitated a lot of peer review discussion which could have also resulted in great grades. Additionally, this performance could have been due to an introduction of the "Office Hour" policy that might have individually helped students to understand certain confusing principles.

Question number	Mean	+/- Standard deviation	Low score	High score
Number 1	**6.5**	**2.02**	**3**	**10**
Number 2	**8.1**	**1.35**	**5**	**10**
Number 3	**8.3**	**1.33**	**6**	**10**
Number 4	**8.1**	**1.30**	**6**	**10**
Number 5	**6.5**	**2.02**	**3**	**10**

Table 6: Midterm exam statistics

Figure 22: Candidates during one of the class presentations for the homework tasks

However, in general candidates performed well in almost all questions with a cumulative performance of 70+/-15 out of 100, apart from some minor mistakes that diverted the principle and their final answers. Candidates proved that they understood the resistive circuit analysis well in addition to the methods used in solving such DC circuits.

5.2.2 Component 2: Electrical circuits labs

Candidates' performance was generally good with a cumulative performance of 17.5+/-2 out of 20. However, analysis of data tended not to be done sufficiently well to gain all of the marks for this criterion but this analysis kept on improving with more labs done.

Table 7: Lab 1 performance

Criteria	Mean	+/- Standard deviation	Low score	High score
Aim(s)	1	0	1	1
Applying knowledge and understanding of circuits	3.9	0.42	2	4
Selecting circuit components and equipment	2	0	2	2
Procedure	1	0	1	1
Processing and presenting data/information	3.76	0.61	2	4
Analyzing data/information	1.88	0.33	1	2
Conclusion(s)	1	0	1	1
Evaluation	2.88	0.33	2	3
Presentation	2	0	2	2

Table 7 indicates lab 1 analysis that portrayed a great mean and standard deviation score for the following criteria – Aim, Selecting circuit components and equipment, procedure, conclusion and presentation.

Table 8: Lab 2 performance

Criteria	Mean	+/- Standard deviation	Low score	High score
Aim(s)	1	0	1	1
Applying knowledge and understanding of circuits	3.9	0.42	2	4
Selecting circuit components and equipment	2	0	2	2
Procedure	1	0	1	1
Processing and presenting data/information	3.76	0.61	2	4
Analyzing data/information	1.88	0.33	1	2
Conclusion(s)	1	0	1	1
Evaluation	2.88	0.33	2	3
Presentation	2	0	2	2

Table 8 indicates lab 2 analysis that portrayed an identical performance to the previous lab 1 with a great mean and standard deviation score for the following criteria – Aim, Selecting circuit components and equipment, procedure, conclusion and presentation. Lab 1 and 2 were similarly performed with a cross-cutting challenge of data analysis.

Table 9: Lab 3 performance

Criteria	Mean	+/- Standard deviation	Low score	High score
Aim(s)	1	0	1	1
Applying knowledge and understanding of circuits	3.79	0.42	2	4
Selecting circuit components and equipment	2	0	2	2
Procedure	1	0	1	1
Processing and presenting data/information	3.61	0.70	2	4
Analyzing data/information	1.88	0.33	1	2
Conclusion(s)	1	0	1	1
Evaluation	2.88	0.33	2	3
Presentation	2	0	2	2

Table 9 indicates lab 3 analysis that portrayed a great mean and standard deviation score with a cumulative performance of 17+/-2 out of 20. Similarly, the following criteria – Aim, Selecting circuit components and equipment, procedure, conclusion and presentation were well performed.

5.3 Areas which candidates found demanding

5.3.1 Component 1: Midterm Exam

Although the exam was well done, some candidates assumed similar questions to the homework or revision sessions and struggled to get previous answers. This was very unfortunate because some of them cancelled the right solutions and embarked on working towards the previous homework answers. As usual, there were also some common mistakes made during calculations especially switching current flow directions and voltage polarities. A few candidates complained about the insufficient time probably due to a poor time allocation for each question.

5.3.2 Component 2: Electrical circuit labs

Although all these labs seemed to have been performed well, the 3-hour time window per week was quite limiting for some candidates to appreciate practically well. This challenge resulted into just copy and paste without any logical reasoning. There were also some times when the equipment and cables would malfunction hence causing delays and unsatisfactory data acquisition. Additionally, this challenge justifies the need for a dedicated BME lab that would provide ample time for students to internalize their designs and improve their performance.

5.4 Advice for the preparation of future candidates

5.4.1 Component 1: Midterm Exam

Although we discussed several methods of circuit analysis, a significant proportion of candidates did not use other methods of solving circuits from the ones that we had used for solving specific homework questions. Additionally, a few candidates used different methods as compared to the specified ones by the question statement. This did not appear to be ability-related but probably little time allocation towards practice for such methods. Candidates need to be given more opportunities to answer with different circuit analysis techniques than is afforded by a single technique alone especially in answering homework questions.

Candidates need to be made aware that there are no different answers to such techniques apart from the method that may either be faster of longer to the final answer.

5.4.1.1 Questions requiring more detailed answers

Questions that require more detailed answers are signaled by the words 'Explain fully' or 'Explain clearly' and are worth more marks than words like "List" or "Explain briefly" Candidates need to be made aware that, to gain full marks for the question, a detailed explanation needs to be given. Additionally, candidates need to be guided by the marks allocated to such questions while answering them. For example, when the weight for a certain question is two marks, candidates would be expected to make at least two correct points within their answer.

5.4.1.2 Calculation of Marks

This chapter contained mark calculations that were taught as part of the course and such calculations highly discriminated each candidate's performance and finally the overall course performance.

Candidates should be encouraged to calculate clearly, as partial credit can often be given to those who fail to gain full credit for the questions. This is particularly true where a concept marking approach is adopted. For example, correctly applied laws or principles were searched for from all questions while assigning partial marks.

5.4.2 Component 2: Electrical labs

Since this was the first time to practice BME related labs by Makerere University BME students, about 4 candidates worked collaboratively in each group and presented a report. Research through verbal questioning indicated that over 80% candidates greatly benefited from this group size leaving the rest with a smaller group preference.

Many candidate reports indicated that candidates would have benefited from greater laboratory engagement than the three weekly allocated hours by the ECE department.

Some reports also showed that candidates had collaborated when processing raw data prior to writing their report. Evidence for this was the same processing mistake appearing in several candidates' reports. This evidence showed an abuse of the instruction to process report data as an individual group instead of a collaborative effort.

5.5 Conclusion

Although this report marked the midterm progress and performance for this biomedical instrumentation electrical circuits class, this analysis will be continued through the second part of the semester. However, the general progress appeared rewarding and proposed better results from the second semester half. This performance was highly supported by the lab activities performed to link the theoretical class notes with the practical lab experience hence strongly supporting the need for a Makerere University BME lab. This is evidently shown by the high mean and low standard deviation marks of lab tables 2, 3 and 4 which resulted in high mean and low standard deviation marks for the midterm exam questions (table 4). Hands on lab experiences convert abstract theoretical student experiences to real life imaginations that in turn improve student understandin

CHAPTER SIX - CONCLUSION

6.0 Introduction:

Chapter six serves as the conclusion chapter for this thesis work. This chapter briefly analyzes the strengths, weaknesses, opportunities and threats (SWOT) for the current Makerere University BME instrumentation course. The chapter finally provides a conclusion and recommendations.

6.1 SWOT ANALYSIS

This chapter evaluates the biomedical engineering instrumentation course capacity to support the growth of the biomedical engineering discipline in Makerere University.

6.1.1 Strengths

6.1.1.1 Competent human resources: There is a pool of highly qualified and skilled personnel from which to leverage the tradition of high quality teaching and research in Makerere University. This pool mainly comes from the college of engineering and the college of health sciences which are key colleges for biomedical engineering. The Makerere biomedical engineering unit has consistently won global innovation awards organized by the University which clearly shows the students' innovative skills, for example the $10,000 big ideas preeclampsia award, $2,000 big ideas first aid postpartum hemorrhage belt, and the $2,500 preeclampsia Duke challenge.

6.1.1.2 Infrastructure: The current lab is located in the college of health sciences under the physiology department with a room size of 7 by 3 meters. This college is conveniently located near Mulago National Referral Hospital which provides a supplementary advantage of space and learning resources for biomedical engineering students. The figures below show the lab setting with some text books and equipment.

Figure 23: Current MUK BME lab

6.1.1.3 Collaborations and partnerships: There exist several multi-disciplinary collaborative arrangements with a wide spectrum of institutions nationally and internationally. These arrangements can be leveraged to build the field of biomedical engineering in teaching, research, technological advancement and innovation. The table 10 below indicates some of these collaborations.

Table 10: Collaborative institutions

Institution	Country
Duke University	USA
Case Western Reserve University	USA
Engineering World Health	USA
Rotary club of West minister	Canada

6.1.2 Weaknesses

There are mainly three weaknesses challenging the current BME instrumentation course. First, there is an inadequate human resource fully responsible for the program development. There is no full time appointed staff which renders all the program services, instead it is currently managed by only part-timers and volunteers. **Secondly, there are constrained financial resources which** is particularly acute given the high cost of training and research in biomedical engineering. For example, BME program lacks dedicated instructional lab benches for the instrumentation class and a budget for the required consumables for these exercises. Finally, there are no basic **biomedical engineering facilities like information and communication technology** (ICT) facilities, fabrication and instrumentation labs needed to support the proper conduct of research and teaching. These three factors greatly affect the BME program, thus compromising the learning opportunities.

6.1.2 Opportunities

6.1.3.1 Lack of enough biomedical engineers: There is a persistent lack of competent biomedical engineers in the country. The creation of novel BME instrumentation course and dedicated biomedical instrumentation track within the BME curriculum will enhance reputable service provision which will enable students to internalize and design electrical circuits thus repairing and rendering useful a vast array of medical equipment that currently lies about in various states of disrepair.

6.1.3.2 Enabling environment: Since health issues are priority factors for many governmental and non-governmental organizations, this lab and its proposed instrumentation curriculum enhancements will provide a great environment for biomedical engineering training and research programs. Uganda is committed to pursuing several health targets including millennium development goals and the college of health sciences (that houses BME) is at the center of this effort.

6.1.3.3 Availability of Institutions/funders who are willing to fund Biomedical engineering related research projects: Organizations like Duke University, Bill and Melinda Gates foundation, and the Uganda National council of Science and Technology are currently funding projects which are aimed at having tangible interventional medical products as deliverables. These are great funding opportunities facilitating many research projects to develop and improve performance.

6.1.3.4 Availability of ready market for our services: As earlier on stated, this lab will pioneer BME labs in Uganda whose need is immensely evident. This need will serve as an opportunity that will engage a virgin and relatively wide market with almost no competition.

6.1.4 Threats

Increased number of BME institutions in Uganda – Although this increase may appear like a positive achievement in Uganda, it may lead to a downfall of this great Makerere BME program. This is because Makerere takes long to implement some vital decisions like lecturer appointment which is contrary to other institutions. Some of the excellent Makerere BME students have been absorbed by these other institutions which may in the long run have a negative impact on this BME program.

6.2 CONCLUSION

During the design, implementation and the evaluation of the Makerere BME instrumentation course, the following key points have been identified in relation to what could have earlier on affected the students' performance. The number of labs performed by students directly affect their theoretical understanding and thus their performance. This is evidently shown by the students' performance in chapter 5 where all students scored above 70% during their midterm assessment. Secondly, the researcher envisioned that the BME instrumentation course would yield greater results once taught by a BME professional than an ECE professional.

Given the above research findings, the researcher strongly recommends the continued funding of a frugal BME lab to support the design, implementation and evaluation of the BME instrumentation course at Makerere University. The researcher additionally hopes to anonymously assess this instrumentation course at the end of the semester so as to obtain a more justifiable deduction.

APPENDICES - RE-DESIGNED LABS FROM DUKE

APPENDIX A - LAB 1: Introduction to Laboratory Measurements

I – Objectives

a) Learn to use the breadboard, power supply, volt-ohm meter, and digital multimeter at your lab station

b) Measure voltages and resistors with your laboratory equipment

c) Learn to record laboratory measurements

d) Learn to measure the accuracy of your laboratory measurements

e) Learn the lab report format

II – Introduction

This lab will serve as a basic introduction of some of the equipment at your lab station, including the breadboard, power supply (Elettronica veneta DC Power Supply), and benchtop digital multimeter (GWinstek, GDM 8034 Multimeter). This equipment will be used to make a variety of voltage and resistance measurements. These measurements are important since the recording of measurements and their accuracy are used in all labs.The accuracy of a measurement is generally defined as the deviation of a measurement from the "true" or ideal value as may be obtained through theoretical analysis or by some standard highly accurate measurement. The absolute error is the difference between the observed value of a quantity and its true or known value. The relative error is the absolute error as a percentage of the true value. Note that absolute and relative errors can be positive (meaning you measured a value larger than the true value) or negative (meaning you measured a value smaller than the true value). A certain amount of random error will occur in all experiments. If a large number of measurements are taken, then random error may average out.

When taking measurements in this class, you will usually have some idea of an expected value, thus every measurement should be accompanied by relative error. Additionally, it is good practice to record the value of the "least count" of the recording instrument. The least count is the magnitude of the smallest marked divisions on the instrument. This number represents the best-case accuracy for that particular measurement. Lastly, while performing the labs you may find reason to deviate from the given procedure. Record the reasoning in your lab notebook. III – Lab Procedure

A) Resistors

1 – For the resistors at your lab station, find the nominal resistance and tolerance of each. For most, use the resistor color code chart shown in Table 1-1. The first and second bands of the color code are the first and second digits of the resistance. The third band of the resistor is the magnitude of the multiplier (note that gold in the multiplier band is 0.1 and silver is 0.01). The fourth color is the tolerance of the resistor. (Note that 1% and better resistors have five or more bands. Just remember that the last band is

always tolerance and the second to last is always the magnitude.) For example, a resistor with color code gray, green, orange, silver would have resistance of $85*10^3$ Ω and a tolerance of 10%. Record the color code and resistance in your notebook.

2 – Next turn on your VOM. Measure the resistance of the each resistor using the Ω setting. Record your measurements. Now turn on the DMM. Making sure that your banana cable leads are in the correct jacks (VΩ and COM) and AUTO is selected (or you have manually selected the correct range for the magnitude of each resistor), measure the resistors from step 1. **How closely do the values you measure match the nominal value?** Estimate the error for each of your VOM and DMM measurements. **Are all of your resistors within tolerance?**

4 – The variable resistor, or potentiometer, can be used to tune electronic circuits because their resistance can be manually changed to any value within a given range. Most "pots" have three terminals and a screw that is turned to vary the resistor. Turn your potentiometer all the way in one direction. Measure the resistance between terminals one and two and between terminals two and three. Add these values together. Repeat these last two steps with the pot turned in the other direction one-third, two-thirds, and all of the way. **What is the range of values to which your pot can be tuned?** Use either the VOM or DMM to make these measurements.

B) Voltages

5 – Turn on your power supply. Set output to produce 6 V. Set your VOM to measure voltage at this output. Now switch the leads of the VOM. What is the measured voltage now?

6 – Now set output to produce 10 V. Measure this output and indicate its reading.

7 – The breadboard is a useful tool for quickly building circuits without soldering. Figure 1-1 shows part of a typical breadboard with a very simple circuit assembled on it. (NB: This circuit has nothing to do with reality. It is just an example of how an assembled circuit might look on a breadboard.)

The breadboard's holes are connected to each other in many separate groups, or nodes, to facilitate building useful circuits. Using the resistance feature of your DMM or VOM, explore the breadboard and determine how its individual holes are interconnected. You should try to force the VOM/DMM's probes into the breadboard sockets. They might fit, but they will do damage. Use a wire and an alligator clip test lead to attach to the breadboard. **Draw a diagram showing the interconnected holes on the breadboard.** This concept will be important throughout the lab sessions.

Figure 1-2 shows the schematic for a simple 3-resistor circuit. Build this circuit on your breadboard. Build this circuit with R1 equal to 270 Ω, R2 equal to 100 Ω and R3 equal to 470 Ω. The power supply should be set to +5 V.

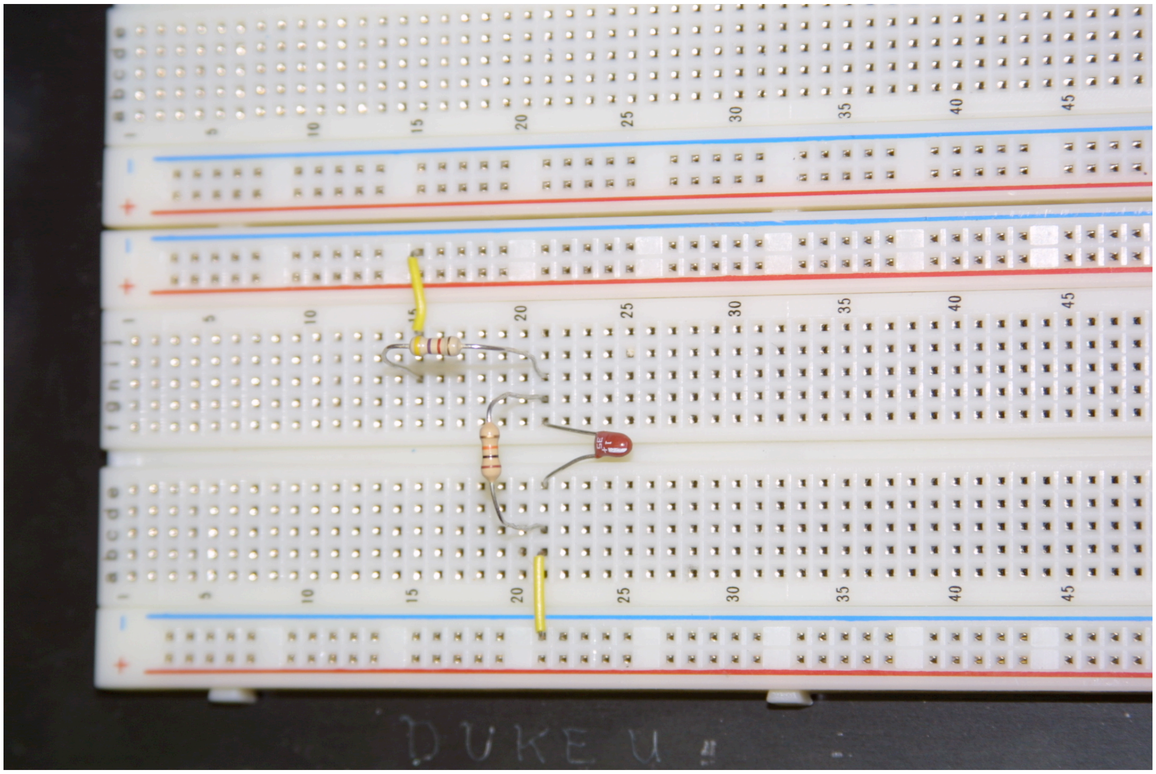
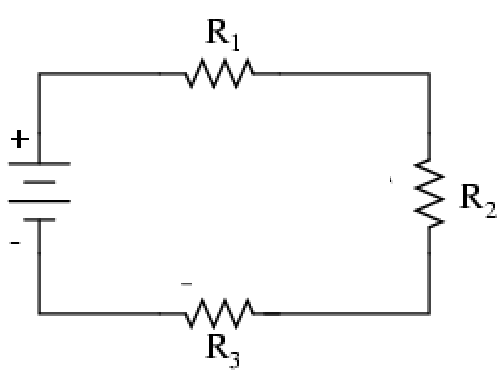


Figure 24-1: Typical breadboard with simple circuit. Circuit shown is for illustration only .



ssFigure 1-25: Three-resistor series circuit

8 – Call the node between the power supply and R1 node A, the node between R1 and R2 node B, the node between R2 and R3 node C, and node between R3 and the

power supply node D. Measure the supply voltage (V), the voltage between node A and B (V_{AB}), the voltage between node B and node C (V_{BC}), and the voltage between node C and node D

(V_{CD}). **What is the difference between V_{AB} and V_{BA}?**

9 – With node D as your reference level (i.e., the COM lead from your VOM is connected to node D), measure the voltages at all four nodes (call them V_A, V_B, V_C and V_D). **Calculate V_{AB}, V_{BC}, and V_{CD} given these measurements?**

10 – Now use node B as your reference level. Measure the voltage at all four nodes. **Are these measurements different than those found in step 9?** What about calculated values of V_{AB}, V_{BC}, and V_{CD}?

APPENDIX B - LAB 2: Ohm's Law and Power

I – Objectives

a) Learn to measure current using the digital multimeter

b) Prove Ohm's Law

c) Measure power indirectly

d) Build a variable voltage divider circuit

II – Introduction

The first lab served as an introduction to the lab equipment while hopefully making you familiar with voltage and resistance measurements. In this lab, we will use the same equipment to measure current and then use the equipment to test some more complex circuits.

Current can be measured two ways in lab. The first, and perhaps easier, is to use the ammeter function on the DMM. It is a little more complex than measuring voltage however. Remember that voltage is measured *across* some circuit element such as a resistor. Current flows *through* a circuit element though and for this reason the ammeter must actually be inserted into the circuit. Figure 2-1 shows how an ammeter might be used to measure the current through a resistor, R2. Note that the ammeter could also be placed into the circuit between R2 and the grounded node. By convention, positive current runs through a circuit element from the positive to the negative voltage node. The other method for measuring current is more indirect and uses Ohm's Law. Before building the circuit, the resistor is measured, and then once the circuit is built, the voltage across the circuit is measured. Application of Ohm's Law yields the current (be sure to maintain the sign convention). This second method is preferred when your circuits become more complex.

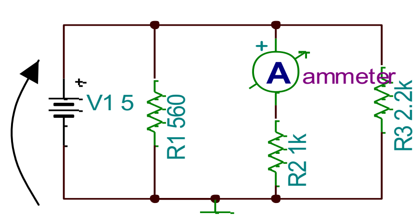


Figure 2-1 **Example circuit showing how an**

The power dissipated by any resistor is merely the voltage multiplied by the current. By using Ohm's Law other equations can be found:

$P = VI$ (1)

But $V = IR$, so (2)

$P = V^2/R$ and (3)

$P = I^2R$. (4)

All electrical devices have maximum ratings for the power that they can dissipate. The maximum power for the standard resistors in this lab is given by the size of the resistor. Most of the resistors that you will use in this class have a limit of ¼ Watt. Your T.A. will tell you the power ratings of other resistors.

III – Lab Procedure

A) Current

1 – Build the circuit in Figure 2-1 (without the ammeter for now). Note that your power supply, V_{in}, should be set to 5 V. To connect your circuit to earth ground, connect the node you want to ground to the grounded jack on your power supply. Now using Ohm's Law, find the current through each resistor. **What is the total current being produced by your power supply?**

2 – Now use the DMM's ammeter function to measure the DC current through each resistor (use the 100mA and COM input jacks). Also measure the total current being

produced by your power supply. **How well do these measurements compare to those made in step one?**

B) Ohm's Law

3 – Now remove R2 and R3 from the circuit and, using your ammeter, measure the current through R1 for several voltage values (V_{in}) between 1 and 10 V. Repeat this experiment using R2 and R3 instead of R1. **With this data, graph current (the dependent variable, y axis) as a function of voltage (the independent variable, x axis)[*].** You should have three curves, one for each resistor. **What does the slope of each curve represent? Do these curves prove Ohm's Law?**

C) Power

4 – Build the circuit in Figure 2-2. With the potentiometer set to a minimum (measure its resistance first), find the voltage across it. Change V_{in} to 8 and 12 V and re-measure the voltage across the pot (V_{out}). Remove the pot from the circuit, turn it a bit and repeat the preceding step several times. For each value of voltage and resistance, find the power being dissipated by the pot. **Graph the power as a function of resistance.** You should have three curves (one for each voltage value). **At what value pot value is the power a maximum?**

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[*] The y axis is also known as the ordinate and the x axis as the abcissa.

D) Variable voltage divider

5 – Figure 2-2 is a voltage divider circuit. The output voltage, V_{out}, is some fraction of the total output from the source, V_{in}=10 V. Build the circuit shown in Figure 2-3 using values of R1 and R2 that you found in Pre-lab. The values that you found in the Pre-lab may not be available in lab so choose replacements such that the output is within 15% of the specification. **For what could a circuit like this be used?** Take a series of measurements to prove that your circuit works.

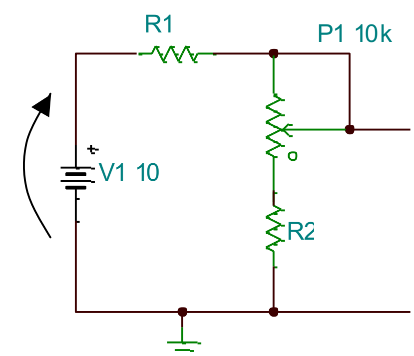
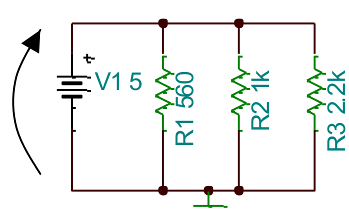


Figure 2-3 **Circuit for step 5. Values for R1 and R2 are to be chosen**

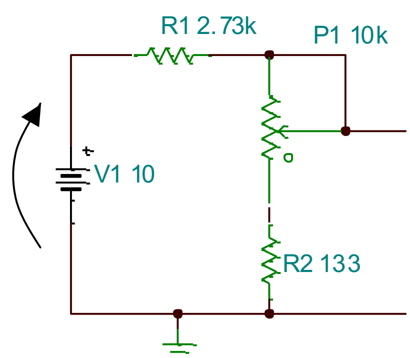
<u>**Pre-lab Questions**</u>

1) What is the current through each resistor in the circuit shown below (to be tested



in Part A of Lab 2)? Are resistors with a maximum power rating of ¼ Watt adequate when building this circuit?

2) The circuit below will be tested in Part D of Lab 2. What values should R1 and R2 be so that as the potentiometer varies between 0 and 10k Ω, V_{out} varies between 0.5 and 8 V?



APPENDIX C - LAB 3: The Wheatstone Bridge and Temperature Measurement

I – Objectives

a) Build and balance a Wheatstone bridge circuit

b) Calibrate a thermistor with a bath at a known temperature

c) Measure unknown temperatures with a calibrated circuit

II – Introduction

The Wheatstone bridge circuit (see Figure 3-1) is widely used in measurement systems. A change in the resistance of one of the arms of the bridge will change the output voltage (V_{out}). In a measurement system, one of the resistors is replaced by a transducer of some type, (R_T). The resistance of the transducer changes in response to a change in another physical parameter. Thus in the Wheatstone bridge measurement circuit, changes in a measurable physical quantity change the output voltage.

An equation for V_{out} can be found by applying Thevenin's theorem to the circuit of Figure 3-1. First the circuit is re-drawn as in Figure 3-2. The Thevenin voltages ($V_{TH1,2}$) and resistances ($R_{TH1,2}$) are then easily found (Figure 3-3).

$$R_{TH1} = R_1 || R_2,\ V_{TH1} = V_{in} * R_2/(R_1 + R_2) \quad (1)$$

$$R_{TH2} = R_3 || R_T,\ V_{TH2} = V_{in} * R_T/(R_3 + R_T) \quad (2)$$

The output voltage can then be defined as $V_{TH1} - V_{TH2}$ (since no current is flowing through R_{TH1} or R_{TH2}).

$$V_{out} = V_{in} * (R_2/(R_1 + R_2) - R_T/(R_3 + R_T)) \quad (3)$$

The Wheatstone bridge can be balanced if (R_1/R_2) = (R_3/R_T). In this case, the output voltage is zero.

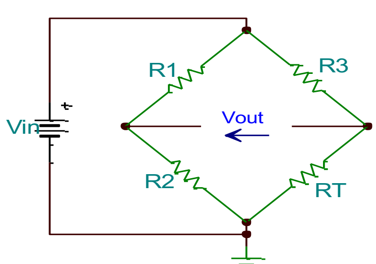


Figure 3-1 The Wheatstone

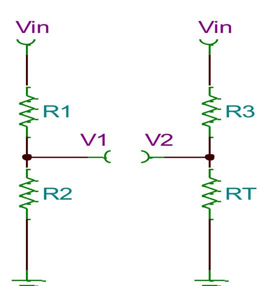


Figure 3-2 Modified bridge

In order to "balance" the bridge in a measurement system, R_2 is replaced by a potentiometer. The pot is varied until the output voltage is 0 V. The resistances of R_1, R_2, and R_3 are assumed to remain constant and the output voltage moves from 0 V only when the physical quantity being measured changes from its value at balancing.

In this lab a thermistor (Omega, part #44033) will be used as the transducer. The resistance of a small semiconductor at the tip of the thermistor changes with temperature. The thermistors used in this lab have a negative temperature coefficient (NTC), meaning as the temperature rises the resistance decreases. The relationship between temperature and resistance may be seen in Figure 3-3. Some reference points are listed in Table 3-1. The slope of the curve is called the sensitivity of the thermistor and is a measure of how a change in input (temperature) affects the output (resistance).

Figure 3-4 and Table 3-1 show that the relationship between temperature

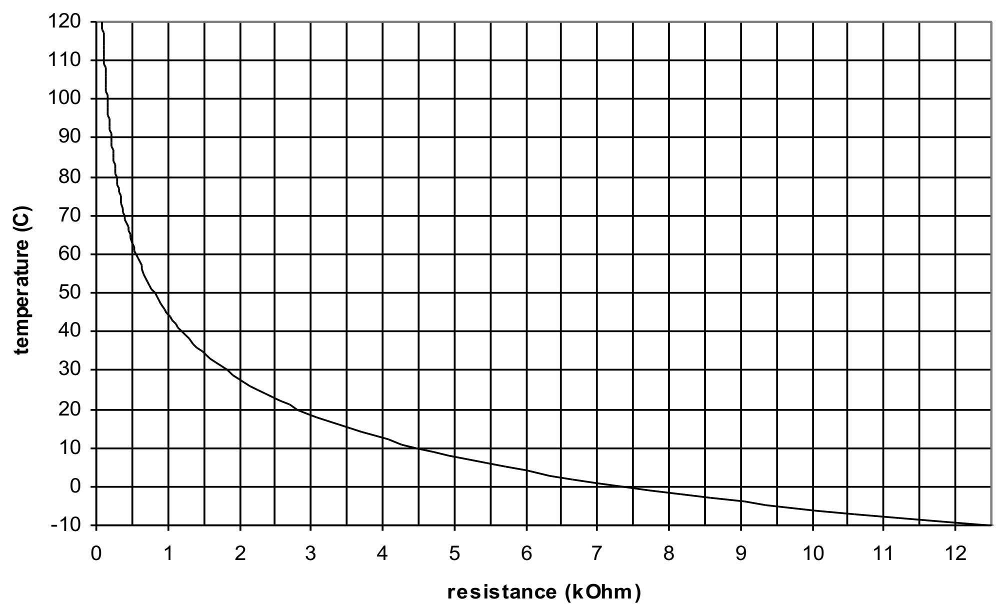


Figure 3-4 Temperature vs. resistance for 44033 thermistor

and resistance is not a simple equation. Therefore, no simple equation relating the entire range of temperature and output voltage exists. Over a small range, though, the relationship may be assumed to be approximately linear. In this lab, the range from 0-25 °C will be measured.

Temperature (°C)	Resistance (Ω)
-10	12.46k
0	7355
25	2252
50	811.3
75	333.1
100	152.8

Table 3-1 Temperature and resistance for some points of interest

III – Procedure

A) The Wheatstone bridge

1 – Build the circuit in Figure 3-5. Since this lab involves liquid (water), a 9V alkaline battery will power circuits. One should be available at each lab station. Using the DMM, ensure the 9V battery has at least 6.5 volts available, and record the initial battery voltage. Connect the battery to a battery snap, and plug the snap leads into your breadboard's power rails (it may help to twist the multi-stranded wire leads into a smooth point). Adjust the potentiometer until the bridge is balanced. **What is the pot's resistance when the bridge is balanced?**

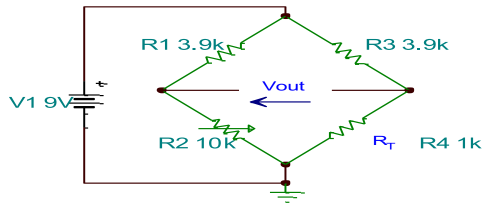


Figure 3-6 Circuit for steps 3-8

2 – Replace R_4 with a 100 Ω resistor. Measure V_{out}. Repeat for 470 Ω, 1.5k Ω, and 10k Ω resistors**. Graph V_{out} as a function of R_4. What kind of function results?**

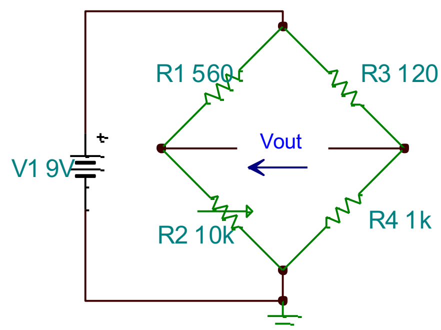


Figure 3-5 Circuit for steps 1-2

3 – Prepare 3 cups of water for use later in the lab. One should be filled with ice water, one with cold tap water, and the last with warm tap water.

4 – Build the circuit in Figure 3-6 with the thermistor as R_T. A jack to receive the thermistor plug should be available. 5 – The measurement circuit will be balanced at 0°C. Measure the temperature of the ice water with the thermometer at your station. It should be at or nearly 0 °C. Place the thermistor in the ice water and wait a few seconds before turning the pot to balance the bridge at 0 V.

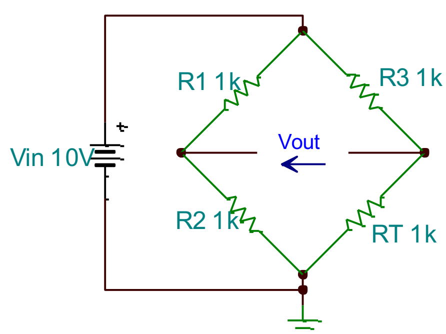
6 – Now measure the output voltage of your measurement circuit for the other two water cups. **Be sure to also record the temperature of the water as measured with the thermometer.** Repeat these measurements. **Are they reliably repeatable?**

7 – Exchange a water cup with another lab group. Measure the output voltage of this water cup. **Given the three calibration points you have found, can you approximate the temperature of the water? What is the sensitivity of your measurement system? Create a graph showing temperature as a function of output voltage.**

Pre-lab Questions

1) What is the temperature of a healthy human body (in °C)? In what range of temperatures can a person stay alive? Provide a reference for your source.

2) Assume that over a small range of temperatures (0-20 °C), the temperature versus resistance curve of a thermistor is linear with slope –0.1 °C/Ω. For the circuit shown below, what is temperature as a function of output voltage? The bridge is



balanced at 0 °C (i.e., at 0°C, the resistance of the thermistor (R_T) is 1000 Ω).

3) For the circuit above, how does the output voltage change if V_{in} = 100 V? Does this change make the measurement system more or less sensitive?

REFERENCES

1. The Emergence of Degree-Granting Biomedical Engineering Programs in Sub-Saharan Africa William Reichert, Brittany Ploss
2. BME coordinators in Ugandan BME institution, J. Ssali (ECUREI), R. Niwareeba (KYAMBOGO), S. Bagayana (MBARARA)
3. http://lautechteachinghospital.org/biomedical.php
4. http://www.who.int/medical_devices/survey_resources/health_technology_national_policy_uganda.pdf
5. https://www.export.gov/article?id=Uganda-Medical-Equipment
6. http://mbl.mak.ac.ug/index.php?option=com_content&view=article&id=28&Itemid=113
7. http://www.oag.go.ug/wp-content/uploads/2016/07/UHSSP-Mainstudy-Final-report-print.pdf
8. ***https://bme.duke.edu/undergrad/prospective***
9. Fundamentals of Electrical Engineering, First Edition, Giorgio Rizzoni; McGraw Hill, ISBN 9780073380377
10. Agarwal, Anant, and Jeffrey H. Lang. ***Foundations of Analog and Digital Electronic Circuits***. San Mateo, CA: Morgan Kaufmann Publishers, Elsevier, July 2005. ISBN: 9781558607354.
11. Earl D. Gates, *Introduction to Electronics*, 4th ed., Thomson, 2004
12. D. C. Green, *Electronics 4,* 3rd ed., Longman, 1995
13. Alan V. Oppenheim, Alan S. Willsky, S. Nawab Nawab, Syed Hamid Nawab, *Signals and Systems* (2nd Edition), Prentice-Hall, 1997
14. S.S. Solimon and M.D. Srinath, *Continuous and Discrete Signals and Systems*(2nd Edition), Prentice Hall, 1998.
15. S. Haykin and B. Van Veen, *Signals and Systems*, John Wiely & Sons, 1999
16. L. Balmer, *Signals and Systems: An Introducti*on (2nd Edition), Prentice Hall Europe, 1997