# Multimeter Design Kit for Circuit Theory Education

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*Abstract*— **One of the most common tools for the practicing electrical engineer is the multimeter. This paper describes a kit that was fabricated for use in laboratory experiments to explore concepts of circuit design and implementation of a simple analog multimeter. The commercial multimeter is a combination of several individual instruments to measure voltage, current, resistance, and capacitance. Common multimeter designs incorporate digital displays. Before the digital age, the world relied on analog displays. Some argue that analog displays are outdated. However, this overlooks one of the most important characteristics of analog displays, which is an immediate visual and qualitative perception based on needle deflection. Analog displays are still used in many applications such as aviation and automotive, demonstrating their continued usefulness. The analog display is based on an electromechanical device called galvanometer. The galvanometer consists of an incrementally marked face and a needle indicator. The needle deflection indicates the intensity of the flow of a small direct current passing through the device. This kit consists of a galvanometer, a ribbon cable with a breadboard connector, three external lead connectors, a 12-position switch and a fuse, all packaged in a 3D-printed enclosure resembling a handheld commercial multimeter. Students use the kit to design a multi-scale DC voltmeter, DC ammeter and AC voltmeter on a breadboard in the circuits laboratory. A parts list and 3D model files are publicly available online for other institutions and individuals to utilize. This project was student-led with close faculty guidance throughout implementation.**

*Index Terms*— Multimeter, Galvanometer, D'Arsonval meter movement, Voltmeter, Ammeter, AC, DC, PCB, 3-D printing, Laboratory, Electromechanical, Multi-scale, Analog, Voltage, Current, Resistance, Needle Deflection, Electrical Engineering

## I. INTRODUCTION

Our multimeter laboratory kit was designed to combine the functionality of a DC voltmeter, DC ammeter, and an AC voltmeter into a single instructional design experiment with the intention of offering a viable and memorable hands-on application of fundamental electrical engineering concepts to supplement the theory. The functionality of the multimeter is obtained by configuring resistor networks in series and parallel with the galvanometer. These networks are implemented on a PB-505 prototyping board. The 12-position rotary switch is used to select its functionality to produce varying scales between the three modes of operation. The various scales provide the user with the ability to adjust the scale of the instrument. This paper is organized as follows: this introduction section is followed by sections on background, design methodology, construction, results, laboratory experiment implementation, conclusion, acknowledgements, and references.

## II. BACKGROUND

The multimeter has been an essential tool for the engineer in practice. As technology has transitioned into the digital age, it has become prevalent within the modern industry to use

digital handheld units. This device made it convenient to obtain all measurements needed from any given circuit using only a single set of probes. Modern designs have become very compact to allow for the electrical engineer in practice to carry a portable one with them with great ease. However, as comfortable and convenient as it is to implement this tool, it is critical for the engineer in training to understand a number of aspects such as the core principles of its operation, the internal components involved, and how the concepts originated in its design. Understanding these aspects develops a deeper appreciation for its usefulness and effectiveness as a tool.

Perhaps the first concept to address is the notion that this tool relies on an engineers visual perception. Modern commonly accepted standards for these devices generally produce a digital readout of the input, and because digital technology has made great strides in recent decades, a fair amount of trust is accepted with the use of this technology. This trust is based merely on countless hours of precision and accuracy testing over a vast range of application spanning decades. However, before digital displays, people relied on analog ones to display some measure of an input stimulus visually. Figure 2 contains two pictures of common multimeters. On the left is an example of a common center-justified analog multimeter. On the right is a Fluke model and is a very typical example of a modern industry-trusted model.

The analog meter that we use is the galvanometer, also called D'Arsonval meter movement. It is a simple tack gauge that experiences deflection when current is passing through it. The intensity of the current determines how much needle deflection is achieved. A representation of this can be seen in Figure 1.
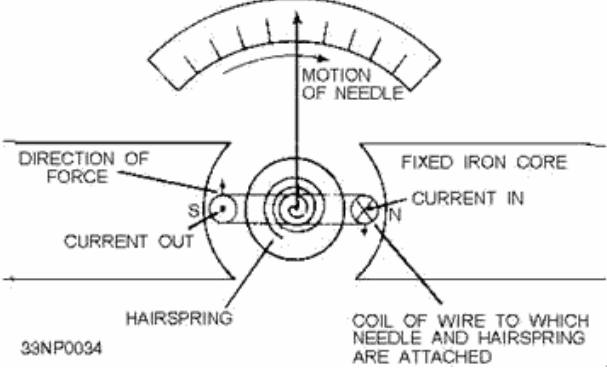


Figure 1. Conceptual representation of the Galvanometers functionality. [8]



Figure 2. Common example of an analog handheld multimeter (Left) [6] and a digital handheld multimeter (Right). [1]

As can be derived from Figure 1, when a direct current is applied to the coil, a magnetic field is generated that responds opposing to the field generated by the permanent magnet located in the center. This subsequently causes the coil to twist and cause measurable needle deflection based on its position with respect to the incremented face of the meter. [2]

A typical galvanometer contains an internal resistance in the order of kiloohms. A full-scale deflection requires a current in the order of microamperes. Based on Ohm's Law, the voltage across the galvanometer at full deflection will be in the order of millivolts. The fundamental mathematical models that govern the functionality of the instrument as part of a multimeter design are Ohm's law, Kirchoff's laws, voltage division, and current division.

The mathematical model for Ohm's Law

establishes that the current ($I$) through a component is directly proportional to the input voltage ($V$) applied across it, divided by its overall internal resistance ($R$). This law is symbolically represented in the following way below in equation (1).

$$I = \frac{V}{R} \qquad (1)$$

As a consequence to these laws, all resistances in series share the same current, and all resistances in parallel share the same voltage.

Voltage division is a technique used to determine the potential voltage drop across a selected resistor ($V_x$) within a given network. It is based on a simple ratio between the selected resistance ($R_x$), the total resistance in the network ($R_t$) obtained via series association, and the applied voltage ($V_s$). It is worth noting that the total resistance ($R_t$) and the source voltage ($V_s$) may also refer only to a particular branch or subsection within a network. Voltage division can be symbolically represented in the following way below in equation (2).

$$V_x = \frac{R_x}{R_t} V_S \qquad (2)$$

Similarly, current division is used to calculate the current in a particular branch ($I_x$) of a network based on the ratio of the total resistance ($R_t$) obtained via parallel association, to the resistance of the branch in question ($R_x$), times the applied current ($I_S$). Current division can be symbolically represented in the following way below in equation (3).

$$I_x = \frac{R_t}{R_x} I_S \qquad (3)$$

These mathematical models and concepts provide the basis for the fundamental understanding and design of the multimeter. Using this basic knowledge the student should be able to construct a design with variable modes of operation with each mode consisting of varying scales to safely measure a range of input stimuli.

A final conceptual requirement of the designer is how this tool is used as a single enclosed unit and how it is subsequently recognized in common schematic designs and application. A medical analogy useful for distinguishing the difference in form between a voltmeter and an ammeter is that a voltmeter can be described as being a non-invasive procedure conducted via a parallel connection with a single component or some subset of the circuit. This parallel requirement is essential following Kirchhoff's voltage law with regards to sharing the same potential as adding another branch to the circuit. The student should also understand that the voltmeter has minimal current passing through it and thus conceptually has a virtually ideal infinite resistance.

The ammeter, on the other hand, can be thought of as an invasive procedure in which one must break the physical circuit and place the unit in a series connection to obtain a measurement. This series connection allows the meter to share the same current passing through it as the series components or nodes following Kirchhoff's current law. By this understanding, unlike the voltmeter, the student should recognize that the ammeter is conceptually designed around a virtually ideal zero resistance, and thus does not impede the flow of current passing through it. Because of the potential to damage an ammeter from passing too much current through it, a fuse is placed in series with the Galvanometer. Standard fuses for most handheld ammeters can withstand up to 0.5A before experiencing filament breakage resulting in an open circuit typically described as a floating connection in design.

The intent was to develop an understanding of the construction and implementation of a multimeter and produce a cost-effective strategy for teaching these aspects to students in a fashion that constitutes a memorable and rewarding hands-on experience. This laboratory experiment kit entails the student's facilitation of the mathematical models for Ohm's law, voltage division, and current division to develop standardized scales and operational modes (verified through calculation and PSpice$^{TM}$ schematic layout simulation) capable of measuring voltage and current inputs of various magnitudes. It also requires a student to prove by design an understanding of Kirchoff's laws in supporting any simulated and physically obtained results. The final objective of this project was to provide the ability for any individual looking for a cost-effective means of building their own portable multimeter a viable solution using the provided materials list, STL formatted models, and a copy of the USM laboratory handout. All of this is made available through a Google$^{TM}$ Drive folder provided and maintained by USM for educational purposes. An overview of all the components required in the construction of a single unit can be seen in Figure 3.



Figure 3. Individual Components

## III. DESIGN METHODOLOGY

The methodology adopted for the construction of the custom enclosure utilized Solidworks$^{TM}$ 3D parametric modeling software produced by Dassault Systemes and 3D printing with PLA for the material of choice for its cost-efficiency and ability to be safely printed in the confined space without any source of ventilation. Solidworks$^{TM}$ was the preferred choice for modeling software because the software's functionality is parametric-based allowing for added convenience when editing designs through several prototyping iterations of the model generation.

For an institution, seeking to utilize parametric-based software without academic licensure could utilize a free cloud-based software called OnShape$^{TM}$. This software was created by members of the original Solidworks$^{TM}$ development team to handle .prt files, which are native only to the Solidworks$^{TM}$ modeling software. For printing purposes, the 3D models were saved as a .stl extension file. A .stl extension file refers to the abbreviated format of stereolithography known as Standard Tessellation Language [5]. Using this format, the model was imported into a slicer for final conversion to a lower form of machine language (formatted as a .gcode file) to be read directly by the 3D-printer. The slicer chosen for a majority of the prototyping was the program called Cura$^{TM}$.

The laboratory kit was designed around the notion that it would incorporate the use of a prototyping board as an extension. This feature allows the student/designer to physically implement their resistor networks on the breadboard during design to accomplish the desired functionality based on some predetermined position of the rotary switch. The 20-pin dual in-line (DIPP) connector, together with a 20-stranded ribbon cable (wire harness), constitute the needed connections for creating the scales and modes of functionality on the PB-505 prototyping board used within the laboratory. Similar to common multimeter designs, the 12-position rotary switch provides the necessary means for easy scale

manipulation based on some pre-mapped radial orientation, and the orientation of the color-coded binding posts follow a typical standard as well.

The final design aimed to incorporate an integrated printed circuit board (PCB) for a portable "plug and measure" type of functionality. This PCB was designed to be mountable on the back plate of the enclosure. The kit was also internally configured with two 9V battery slots integrated into the model of the back plate to provide the necessary enclosable power source for the operational amplifier utilized in the student's design of the AC voltmeter mode of operation. These features give the student/designer the opportunity to take the component networks created for the scales and modes of operation and incorporate them in a finalized design that is completely enclosed.

## IV. CONSTRUCTION

The design is a continuation of work conducted by Alex Wilson, a previous USM electrical engineering student. His work on the project, performed under the close guidance of Dr. Lück, laid the foundation for the development of the final product described here.

The physical construction of the latest model generation began by first fabricating a custom enclosure for the device. This construction was found achievable utilizing additive manufacturing techniques used by common 3D printers. Conceptually, 3D printers function by layer deposition of a thermoplastic material such as PLA or ABS. By current standards, the layer height achievable by the device dictates its overall resolution. Currently available printers are capable of achieving micron-level resolution in the order of 100 microns with an average price tag for such reliable technology ranging from $300.00 to $1,000.00. Higher resolution is achievable, however, as one can imagine with the current limitations of such technology, the cost-

feasibility of such devices for personal and institutional purposes becomes unrealistic for implementation.

The resolution of the printer used for much of the prototyping and finalized designs had an overall highest resolution of 100 microns per manufacturer specification. The final generated STL models were successfully tested to be printable with all embedded model dimensions using a range of layer height between 0.1-0.3mm. Beyond this resolution range, it is possible that issues in recreating the kit may arise from a difference in the printing parameters used and how the front and back parts of the enclosure physically mesh together with one another. This could also apply to the features generated to accommodate the components mounted to the face of the enclosure as well.



Figure 4. Internal View

The specification of any other parameters were not relevant for reproduction of the 3D models provided and is largely based on printer manufacturer specifications and user

preference. Another critical aspect for printing pertains to the orientation of the models when passed through the slicer and saved in a .gcode format. As a rule of thumb for orientation, it is always more advantageous for objects to be printed with minimal over-hanging structures (features), and as further contingent consideration, incorporating minimal features needing additional support material if overhanging structures are inevitable for successful part fabrication.

Once printed, the components list (included with the lab handout) is used to determine the exact size of all hardware and parts required for the kit's assembly. Figure 4 shows an internal view of the meter design kit after all soldering and assembly is completed.

The ribbon cable (wire harness) consists of 20 individual wire connections corresponding to the 20 pins of the connector. The other end of the ribbon connections is then carefully soldered to the positive meter contact, each of the individual rotary switch position contacts, a selector contact, three binding post contacts, a negative fuse contact, and two auxiliary connections left unused for personalized modifications by the designer. A piece of scrap wire and connectors constitute the necessary connection between the negative meter contact and the positive contact of the fuse holder. A pin layout for the DIPP connector can be referenced in Figure 5.

Dual In-line Pin Package (DIPP top view, with the ribbon red stripe up):

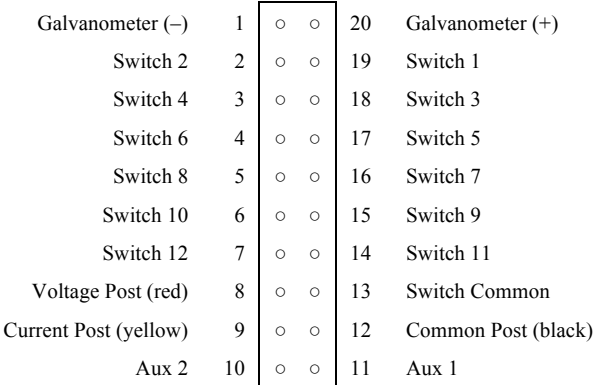| | | | | | |
|---|---|---|---|---|---|
| Galvanometer (−) | 1 | ○ | ○ | 20 | Galvanometer (+) |
| Switch 2 | 2 | ○ | ○ | 19 | Switch 1 |
| Switch 4 | 3 | ○ | ○ | 18 | Switch 3 |
| Switch 6 | 4 | ○ | ○ | 17 | Switch 5 |
| Switch 8 | 5 | ○ | ○ | 16 | Switch 7 |
| Switch 10 | 6 | ○ | ○ | 15 | Switch 9 |
| Switch 12 | 7 | ○ | ○ | 14 | Switch 11 |
| Voltage Post (red) | 8 | ○ | ○ | 13 | Switch Common |
| Current Post (yellow) | 9 | ○ | ○ | 12 | Common Post (black) |
| Aux 2 | 10 | ○ | ○ | 11 | Aux 1 |

Figure 5.  Pinout for the 20-Pin DIPP Connector. [4]

Once all connections are established, the rotary switch can be mounted to the face of the enclosure. A numbered selector plate and a rotary knob are 3D printed using the .stl files provided and fixed in their respective places on the face of the enclosure. A piece of rubber gasket is adhered (using ordinary super glue) in the slot provided on the inside lip of the enclosure to provide a firm grip of the ribbon cable and protect the contacts inside the enclosure. Finally, the back plate of the enclosure can be snapped in place, and hex nuts and screws can be inserted into each of the four corners and torqued hand-tight.

## V.  RESULTS

The design offers the scaled functionality of a DC voltmeter, DC ammeter, and an AC voltmeter.

As an extension, this would also include the STL files for the 3D printed enclosure, rotary knob, and switch position reference plate. The primary educational implementation of the design experiment can be seen in Figure 6 where the 20-pin DIPP connector is plugged into the PB-505 prototyping board.

Also seen in Figure 6 is a network of resistors in series and parallel, routed through appropriate pins of the DIPP connector according to a particularly desired layout. These connections are what comprise the needed scales for the different functions. Once all scales are verified, a PCB can be fabricated with the necessary components and mounted on the back plate to produce an entirely enclosed and portable meter design.

Figure 6. A Sample Design Implementation

## VI. LABORATORY EXPERIMENT IMPLEMENTATION

The laboratory experiment consists of two parts. Part 1 is entitled Preliminaries. This part requires the student to research various aspects regarding the history, characteristics, and operation of the galvanometer. It furthers requires the student to develop a conceptual understanding of its use as a DC voltmeter and DC ammeter.


Figure 7. Circuit diagram of the complete circuit design.

The final concepts to be addressed by the student pertain to the galvanometer's use as an AC voltmeter. Figure 7 includes a schematic representation of the circuit needed to allow for such AC functionality in this experiment. This circuit provides a half wave rectification of the AC input signal to prevent the needle of the meter from deflecting in the negative direction. Conceptually, the design is only interested in observing the top half of the ac

waveform for the AC input stimulus. It is worth noting that there are analog meters capable of deflecting in both directions by being center justified. The model used in this kit is left justified with respect to the resting equilibrium position of the needle indicator.

## VII. CONCLUSION

This design provides many key features. Educationally, it provides the individual with a hands-on understanding of this standard multi-tool. Successful design and implementation require the knowledge and application of fundamental circuit theory. Specifically, the concepts crucial to design are those of voltage division, current division, Ohm's Law, and Kirchoff's law to be realized physically. This process, in turn, reinforces the theoretical concepts learned in lecture and provided a thorough understanding of this tool beyond its simple operation.

Another key feature of this design pertains to its cost-effectiveness. This design provides a viable option for those who share the same passion for engineering as we do and desire a cost-efficient means for obtaining such an essential tool with an overall price tag of roughly $25.27 per unit (individual prices of components subject to change).
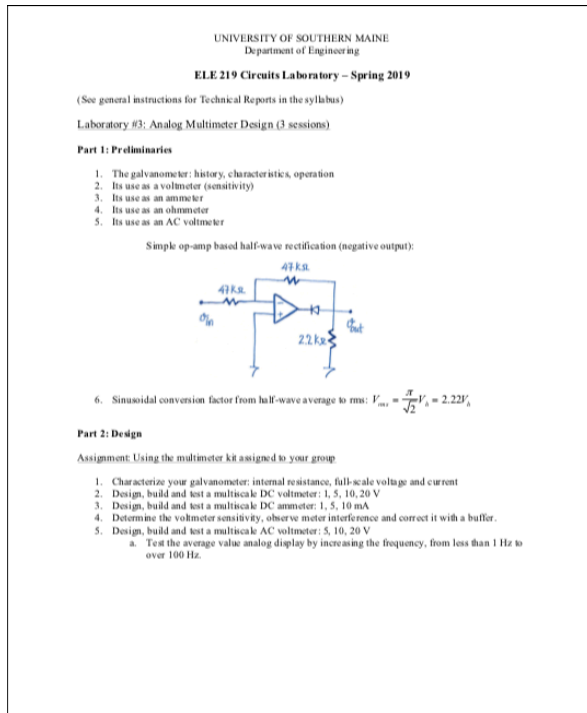
Figure 8. Laboratory handout provided to the students. [4]

A complete list of all components and where to obtain them are provided as part of the laboratory for students to pursue the option of constructing one for them to retain for their personal uses. The kit is graciously made available by University of Southern Maine Engineering department through a Google Drive folder maintained for educational purposes at https://drive.google.com/drive/folders/11-M5BOZSZOnvVUSp3VZlTMdBq6YeIQb6?usp=sharing.

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We would also like to extend our sincere appreciation to Alex Wilson for all of his previous work. His contributions were monumental in establishing the foundation for this project, and we hope others will continue to do the same with what we have done here in the effort of furthering engineering education.

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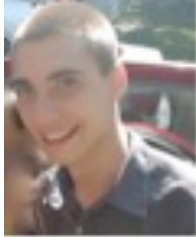[3]TINA. (n.d.). TINA - Analog, Digital, MCU & Mixed Circuit Simulator. Retrieved January 8, 2019, from https://www.tina.com/

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