DESIGN AND CONSTRUCTION OF A METER BRIDGE: A COMPARATIVE STUDY TO DETERMINE THE UNKNOWN RESISTANCE OF A CONSTANTAN WIRE USING ALUMINUM, STEEL AND COPPER PLATES

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BENIN CITY, NIGERIA.

NOVEMBER, 2025

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A PROJECT SUBMITTED TO THE DEPARTMENT OF PHYSICS, FACULTY OF PHYSICAL SCIENCES, IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF BACHELOR OF SCIENCE DEGREE IN PURE AND APPLIED PHYSICS, UNIVERSITY OF BENIN, BENIN CITY, NIGERIA.

NOVEMBER, 2025

CERTIFICATION

This is to certify that the work contained in this project report was carried out by Marcus Oluchi Esther, PSC2105511, of the Department of Physics, Faculty of Physical Sciences.

It has been read through and approved by Dr O. M. AWODU (Project Supervisor) of physic department, Faculty of Physical Sciences, University of Benin, Benin-City, Nigeria.

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Dr O. M. AWODU **(Project supervisor)**	**DATE**
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PROF. C. O. AIGBOGUN **(Head of Department)**	**DATE**

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EXTERNAL SUPERVISOR **DATE**

DEDICATION

I dedicate this work to my uncle, my sponsor, whose generous support and belief in me made this journey possible. To my big mummy, for her endless love, guidance, and encouragement that lifted me in moments of doubt. To my parents, for their prayers, care, and unwavering faith in me, which have been my constant strength. To my younger sister, Favour, whose cheerfulness and inspiration brightened even the toughest days. To my entire family, for being my foundation and source of resilience throughout this journey. Finally, I dedicate this work to all who strive to overcome challenges and pursue their dreams may this serve as a reminder that persistence, faith, and the support of loved ones can turn every obstacle into a stepping stone.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to God Almighty for His grace, wisdom, and strength that enabled me to complete this project successfully.

Special thanks go to my supervisor, Dr O.M. AWODU, whose guidance, patience, and constructive advice greatly assisted me throughout the course of this project. His support during the research and report writing stages is deeply appreciated.

I would also like to acknowledge with much appreciation the assistance of Mr. Oni, for his help during the construction of my meter bridge and for granting me access to use the necessary laboratory tools and equipment.

My heartfelt thanks go to my uncle, Mr. Sunday Ayegbeni, for his love, sponsorship, and for never giving up on me. I also appreciate my Big mommy,Mrs Mary Umoru, for her care, encouragement, and unwavering support, and my parents, Mr and Mrs Marcus for their love, prayers, and sacrifices throughout my academic journey. I also appreciate my younger sister, Favour for her love, encouragement and support throughout this journey, as well as a friend who supported me at the start of this journey, whose encouragement is warmly remember.

Finally, I extend my gratitude to my friends and colleagues for their cooperation and support, and to all who contributed in one way or another to the success of this work.

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ABSTRACT

This project focuses on the design, construction, and experimental analysis of three distinct meter bridges fabricated using aluminum, steel, and copper base plates. The primary objective was to measure and compare the internal resistance of a constantan wire using these three different conductive materials, and to analyze how the type of base metal affects the accuracy, sensitivity, and stability of resistance measurements. The study is based on the fundamental principle of the Wheatstone Bridge, which provides a reliable method for comparing and determining unknown resistances by achieving a state of balance between two arms of an electrical network. The meter bridge, being a modified form of the Wheatstone bridge, was selected due to its simplicity, accuracy, and wide applicability in electrical measurement laboratories. During fabrication, each meter bridge consisted of a one-meter uniform wire mounted on a polished metal base (aluminum, steel, or copper), fitted with thick brass strips, standard resistors, binding posts, and a jockey for variable contact. A Leclanché cell served as the power source, and a center-zero galvanometer was employed to detect the balance point. Constantan was chosen as the test wire due to its negligible temperature coefficient of resistance and high mechanical stability. Experimental readings were taken for various known resistances, and the corresponding balance lengths were recorded. The internal resistance of the constantan wire was computed and analyzed. The results revealed that the copper-based meter bridge exhibited the highest sensitivity and accuracy, with minimal contact resistance losses, while the steel-based bridge showed the greatest deviation due to higher resistivity and surface oxidation. The aluminum-based bridge demonstrated moderate performance, balancing between sensitivity and durability. The study concludes that the material used for the construction of a meter bridge significantly influences the measurement precision, internal resistance losses, and thermal stability. Among the three prototypes, copper is recommended as the most efficient base material for precision resistance measurement, while aluminum offers a cost-effective alternative for educational purposes. This project therefore provides both theoretical insight and practical guidance for designing low-cost, accurate, and reliable electrical measuring instruments suitable for physics laboratories and engineering workshop

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

A meter bridge is an essential laboratory instrument that operates based on the principle of the Wheatstone bridge, which enables the precise measurement of unknown resistances through the balancing of two legs of a bridge circuit (Horowitz and Hill, 2015). The original concept of the Wheatstone bridge, developed by Samuel Hunter Christie in 1833 and popularized by Sir Charles Wheatstone in 1843, forms the theoretical foundation of the meter bridge (Kumar and Singh, 2012).

In a meter bridge, a one-meter-long uniform resistance wire is stretched over a calibrated wooden or metallic base, allowing users to determine unknown resistances by finding the point where a galvanometer shows zero deflection (Agarwal, 2013). This principle of a “null method” offers higher accuracy because it does not depend on the calibration of the galvanometer but rather on the balancing of resistances (Serway and Jewett, 2018).

The design of the meter bridge incorporates a resistance wire with uniform cross-sectional area and resistivity, conditions necessary to ensure that the resistance is directly proportional to the length of the wire (Hambley, 2011). Such proportionality simplifies calculations, allowing the unknown resistance to be determined by simple ratios involving known resistances and measured lengths along the wire (Griffiths, 2017). In practice, the bridge is equipped with a jockey, a sharp metallic contact, which moves along the resistance wire to locate the balance point with minimal disturbance to the circuit (Luo et al., 2019).

To minimize errors, good construction practices demand that the contact resistance between the jockey and the wire be negligible and that the wire remains tightly stretched and free from temperature-induced resistance changes (Horowitz and Hill, 2015).

The concept of measuring electrical resistance dates back to the early days of electricity. The meter bridge was developed as a practical tool to facilitate the understanding of electrical measurements. Its design is rooted in the works of renowned scientists such as George Simon Ohm, who established the relationship between voltage, current, and resistance. Understanding this relationship is crucial for students and professionals in physics.

The meter bridge is widely used in introductory and advanced physics laboratories because it offers a tangible method of studying Ohm's Law and the concept of electrical resistance in conductive materials (Kumar and Singh, 2012). It not only aids students in understanding theoretical electrical concepts but also builds practical skills in circuit assembly and precision measurement (Agarwal, 2013). Moreover, the apparatus is relatively inexpensive, easy to construct, and highly reliable when used under controlled experimental conditions (Serway and Jewett, 2018).

The meter bridge is specifically designed and constructed to determine the resistance of a constantan wire, a material known for its stable resistivity under varying temperatures (Griffiths, 2017). Constantan, an alloy of copper and nickel, exhibits minimal change in resistance with temperature, making it ideal for precision resistance measurements (Luo et al., 2019). The choice of constantan thus reduces potential errors related to thermal effects, which could otherwise affect the accuracy of the meter bridge method (Horowitz and Hill, 2015). Additionally, the study of constantan resistance highlights important materials science concepts, such as temperature coefficients of resistance and the design of alloys for specific electrical properties (Kumar and Singh, 2012).

Beyond measuring resistance, constructing the meter bridge offers valuable insight into practical aspects of electrical design, such as ensuring low-contact resistance, maintaining mechanical stability, and minimizing parasitic capacitances (Agarwal, 2013). Furthermore, the application of the meter bridge in determining unknown resistances lays the groundwork for more advanced topics, including network theorems, impedance measurement, and the operation of more complex bridge circuits like the Maxwell Bridge and Kelvin Bridge (Hambley, 2011).

Overall, the construction and use of the meter bridge to determine the resistance of a constantan wire is not merely an exercise in measurement but a comprehensive application of physics, engineering principles, and materials science (Griffiths, 2017). By undertaking this project, a deeper understanding of electrical resistance, experimental design, and scientific reporting will be achieved, reinforcing both theoretical and practical aspects of physics education (Luo et al., 2019).

1.2 Types of Meter Bridge and Contributions of Notable Researchers

The meter bridge, a practical adaptation of the Wheatstone bridge, exists in various forms tailored to different experimental and industrial applications. The commonly used types include:

i. Slide-wire meter bridge
ii. Digital meter bridge
iii. Modified analog versions

Each type has evolved to improve sensitivity, accuracy, and ease of use in specific contexts.

Slide-Wire Meter Bridge Used primarily in educational settings, it is simple to construct and cost-effective. However, it is prone to human error, and its accuracy depends on the uniformity and cleanliness of the resistance wire.

Digital Meter Bridge Applied in research and industrial labs, it provides high precision and real-time results. While more expensive, it reduces human error and allows for broader measurement ranges (Hughes and Smith, 2012).

Modified Analog Meter Bridge Tailored for rugged environments or specialized applications, these bridges can be adapted for field diagnostics and customized experiments.

1.3 Overview of Electrical Measurement Techniques

Electrical measurement techniques involve methods and instruments used to determine the values of electrical quantities such as current, voltage, resistance, capacitance, and inductance (Mehta and Mehta, 2010). These techniques are essential for the design, analysis, testing, and maintenance of electrical circuits and systems. Measurements can be performed using analog instruments like ammeters, voltmeters, and galvanometers, or digital devices such as multimeters and oscilloscopes, depending on the required accuracy and nature of the signal (Boylestad, 2013).

In fundamental experiments, null-deflection methods, such as the Wheatstone bridge and its practical adaptation in the meter bridge, are widely used because they offer high precision by minimizing the effect of instrument errors. Advanced techniques may involve electronic signal conditioning, data acquisition systems, and computer-based analysis for complex circuits.

Accurate electrical measurements are crucial for ensuring the performance, safety, and efficiency of both laboratory experiments and real-world engineering applications (Mehta and Mehta, 2010).

1.4 Importance of a Meter Bridge for Education and Research

The meter bridge plays a fundamental role in education by helping students understand essential principles of electrical circuits, including Ohm’s law, Kirchhoff’s laws, and the Wheatstone bridge balancing technique (Halliday et al., 2014).

Through hands-on experiments with the meter bridge, learners develop practical skills in accurate resistance measurement, error minimization, and critical thinking related to circuit analysis (Arora, 2001).

In research settings, the meter bridge offers a simple yet highly precise method for evaluating material properties, especially in the study of conductive materials like constantan, manganin, and nichrome. It also aids researchers in calibrating instruments and validating theoretical models where precise resistance values are necessary.

The meter bridge remains a valuable tool because it teaches the importance of sensitivity, null measurement techniques, and experimental verification all of which are foundational in advanced physics and electrical engineering research (Halliday et al., 2014).

1.5 Factors That Govern Meter Bridge

I. Uniformity of the Bridge Wire

- The resistance wire must have uniform cross-sectional area and resistivity throughout its length.
- Any variation can distort the proportionality between length and resistance, leading to incorrect results.

II. Contact Resistance

- Poor contact at junctions (between wire and terminals or the jockey) introduces extra resistance, which can affect the balance point.
- Clean, tight connections help reduce this issue.

III. Temperature Effects

- Resistance of the bridge wire and components increases with temperature.
- Heating of the wire due to current can cause expansion or change in resistivity, affecting accuracy.
- Use low, steady current to minimize heating.

IV. Sensitivity and Calibration of the Galvanometer

- A highly sensitive galvanometer allows for better detection of the null point (zero deflection).
- Proper calibration ensures that the null point corresponds accurately to the length ratio.

V. Thickness and Type of Wire

- The material and diameter of the bridge wire affect its resistance per unit length.
- Common choices are constantan or nichrome due to their low temperature coefficients

VI. Jockey Pressure and Sharpness

- The jockey tip should be sharp and apply minimal pressure to avoid damaging the wire or creating inconsistent contact.
- A blunt or dirty tip can shift the actual null point.

VII. Precision in Measuring Balancing Length

- The accuracy in reading the position of the null point (typically using a meter scale) affects the final resistance value.
- Avoid parallax error when reading the scale.

VIII. End Correction

- The bridge wire may not start exactly at 0 cm or end exactly at 100 cm due to terminal thickness.
- An end correction is sometimes applied to account for this.

IX. Symmetry of Setup

- For better accuracy, use comparable resistors (not widely different) in both gaps to ensure balance near the middle of the wire.
- This helps improve sensitivity around the null point.

1.6 factors that affect meter bridge

There are numerous errors that associated with Meter Bridge which may be caused by:

i. The degree of sensitivity of the galvanometer used in the meter bridge, which affects the accuracy of balance point.

ii. Variation of the E.M.F. of the battery used in the measurement, which influence reading and therefore affects results badly.

iii. The inability to balance the bridge to the required precision.

iv. An accumulation of small errors resulting from practical circuit and construction problems for examples, non-uniformity of the bridge.

v. The wire used (often constantan or manganin) must have uniform resistivity and diameter. Any variation causes inaccurate readings due to non-uniform resistance.

vi. Excessive pressure while sliding the jockey can deform the wire, altering resistance locally. Also, inaccurate placement of the jockey affects precision.

vii. Any movement or shaking during measurement can disturb the jockey position and affect the reading.

viii. Misreading the scale due to incorrect eye positioning leads to inaccurate determination of the null point.

ix. Poor connections at the terminals or between the jockey and the wire introduce extra resistance, causing errors in null point detection

x. Resistance of the wire changes with temperature. Heat from the environment or current flow can increase the wire's resistance, affecting measurements.

xi. Worn-out, oxidized, or corroded wire affects conductivity and thus alters the resistance distribution along the wire.

1.7 Problem Statement

In the Department of Physics at the University of Benin, many students struggle to fully understand electrical measurement concepts due to limited access to practical laboratory tools. While theoretical knowledge is emphasized in lectures, there are few opportunities to apply these principles through hands-on experiments. This often leads to difficulties in grasping key topics such as resistance measurement and circuit analysis.

To bridge this gap, this project involves the design and construction of a meter bridge, a simple but effective instrument used to measure unknown resistance. By building and using the meter bridge, students gain practical experience that helps connect theoretical concepts with real-world application. This approach not only improves understanding but also builds critical thinking and problem-solving skills essential for future work in physics.

1.8 Justification

Fabricating a meter bridge entirely from locally sourced materials not only enhances accessibility for practical laboratory sessions but also provides students with a hands-on opportunity to engage deeply with the instrument gaining insight into its construction, operational principles, and inherent limitations. This initiative strongly supports the department's commitment to cultivating technical proficiency and problem-solving skills among final-year students.

1.9 Purpose of the Study

This purpose of this project to design, construct, and evaluate a fully functional meter bridge capable of accurately measuring the resistance of a constantan wire within a controlled laboratory environment. The ultimate goal is to ensure both precision and reliability in resistance measurement through a hands-on, application-based approach.

1.10 Limitation of the Study

This project is restricted to the design and construction of a simple meter bridge without any digital automation or integration. Factors such as temperature variations, contact resistance, and human errors during measurement may slightly impact its accuracy.

1.11 Significance of the Study

This project serves as a valuable pedagogical resource, particularly within undergraduate physics laboratories, where hands-on experimentation plays a crucial role in bridging the gap between theoretical concepts and real-world applications. By engaging students in the design, fabrication, and practical utilization of a meter bridge, the project reinforces foundational principles of electrical measurement, such as Ohm’s law, the Wheatstone bridge principle, and the behavior of resistive materials like constantan wire.

The incorporation of this project into the academic curriculum provides a platform for experiential learning, where students are actively involved in constructing laboratory instruments rather than solely relying on pre-assembled equipment. This approach enhances the depth of understanding of core electrical concepts by allowing learners to visualize and manipulate physical components, observe the outcomes of their design decisions, and make critical adjustments based on empirical feedback.

Furthermore, the project fosters a range of technical competencies including accurate soldering, material selection, circuit design, and instrumentation calibration. It also nurtures essential soft skills such as analytical reasoning, collaborative teamwork, and effective problem-solving skills that are highly transferable to both academic research and engineering practice. As students work through the challenges of assembling a functional meter bridge and ensuring its precision, they cultivate a deeper appreciation for measurement accuracy, experimental integrity, and the practical constraints often encountered in real-life laboratory settings.

Ultimately, this project not only enriches the educational experience by integrating theoretical knowledge with hands-on application but also prepares students for more advanced experimental work and research endeavors. By promoting autonomy, creativity, and engineering-minded thinking, it contributes meaningfully to the holistic development of future physicists, engineers, and technologists.

1.12 Scope of the Study

This study focuses on the design and construction of a functional meter bridge and its use in determining the resistance of a constantan wire. It excludes the analysis of complex resistive networks, advanced bridge configurations, and systems involving microcontrollers.

The following boundaries are defined:

- The test wire is constantan, chosen for its relatively stable resistance over temperature.
- The project involves measuring internal resistance using the balance method of the Wheatstone bridge.
- Comparative analysis includes parameters such as measurement accuracy, stability, ease of fabrication, and cost.

- Environmental effects such as humidity and long-term corrosion are only briefly considered but not deeply analyzed.
- Electronic noise, advanced digital measuring systems, and thermal conductivity measurements are outside the scope of this study.

1.13 Aim and Objectives

The aim of this project is to design and construct a meter bridge and use it to determine the internal resistance of a constantan wire.

The objectives of this project are to:

1. Understand and analyze the operating principle of the Wheatstone bridge.
2. Build a functional meter bridge using locally sourced and readily available materials.
3. Apply the fabricated meter bridge in the precise determination of the internal resistance of a constantan wire.
4. Assess the accuracy, reliability, and performance efficiency of the constructed meter bridge.

1.14 Project Organization

i. Chapter One: Introduction
ii. Chapter Two: Literature Review
iii. Chapter Three: Methodology
iv. Chapter Four: Results and Discussion
v. Chapter Five: Conclusion and Recommendations

CHAPTER TWO

LITERATURE R EVIEW

2.1 Introduction to Electrical Resistance Measurement

The measurement of electrical resistance constitutes a fundamental aspect of both experimental and applied physics, as well as electrical engineering. The ability to determine the opposition that a conductor presents to the flow of electric current is critical for material characterization, circuit design, fault diagnosis, and the calibration of precision instruments. In practical terms, resistance measurement enables the evaluation of conductor properties such as resistivity, temperature coefficient, and stability under operational conditions.

Historically, resistance measurement evolved alongside the development of electrical science in the nineteenth century. Early pioneers such as Georg Simon Ohm, who formulated Ohm's law in 1827, established the mathematical relationship between current, voltage, and resistance. Subsequent advancements in instrumentation facilitated the transition from rudimentary galvanometric methods to bridge circuits that provided higher precision and reduced error margins.

Among various techniques developed for resistance measurement, the Wheatstone bridge and its derivative, the meter bridge, have been widely adopted in educational and research laboratories. These instruments are valued for their balance method, which nullifies the effect of the measuring device's own resistance, thereby enhancing accuracy. The design simplicity and adaptability of the meter bridge make it an enduring tool in laboratory settings.

The fabrication material of the meter bridge's structural components, including its contact plates, significantly influences its long-term accuracy, mechanical durability, and maintenance requirements. This study focuses on three metallic plate materials: aluminum, steel, and copper, each possessing distinct electrical and mechanical properties that potentially affect the performance of the instrument in a laboratory environment.

2.2 Historical Development of the Wheatstone Bridge

The Wheatstone bridge, upon which the meter bridge is based, was first described in 1833 by Samuel Hunter Christie. Christie's arrangement, though conceptually sound, did not gain widespread recognition until Sir Charles Wheatstone improved and popularized it in 1843. Wheatstone's modifications included refining the arrangement of the bridge arms, incorporating a galvanometer, and advocating for its use in precision resistance measurements.

The fundamental design of the Wheatstone bridge consists of four resistive arms arranged in a quadrilateral configuration, with a galvanometer connected between two opposite junctions. A voltage source is applied across the remaining two junctions. The bridge achieves balance when the ratio of resistances in one pair of opposite arms equals the ratio in the other pair, resulting in zero current through the galvanometer. This balance condition can be expressed mathematically as:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \qquad (2.1)$$

Where $R_1, R_2, R_3 and R_4$ represent the resistances in the four arms.

In the mid- to late-nineteenth century, the Wheatstone bridge became the preferred method for calibrating resistance standards, determining unknown resistances, and evaluating the resistivity of new materials. It was extensively used in telegraphy to detect line faults by identifying resistance changes along transmission wires.

During this period, the construction materials of the bridge's conductive elements played a critical role. Brass and copper were commonly used due to their good conductivity and workability, although corrosion presented a persistent challenge. This historical consideration foreshadows the modern-day interest in optimizing materials for meter bridge fabrication, the focus of the present study.

2.3 The Wheatstone Bridge Principle

The Wheatstone bridge, first popularized in the mid-19th century, is a fundamental electrical circuit configuration employed for precise resistance measurements (Maxwell, 1873). Conceptually, the Wheatstone bridge consists of four resistive arms arranged in a diamond-shaped circuit, with a galvanometer connected across one diagonal and a voltage source across the other. At balance, the potential difference across the galvanometer is zero, and the ratio of the two known resistances is equal to the ratio of the unknown resistance and the variable arm.

Mathematically, the balance condition is expressed as:

$$\frac{R_1}{R_2} = \frac{R_x}{R_3} \qquad (2.2)$$

Where

R_1 and R_2 are known resistances,

R_x is unknown resistance

R_3 is the variable or adjustable resistance.

The precision of the Wheatstone bridge depends on the stability of the components, the sensitivity of the galvanometer, and the skill of the operator in achieving a balanced condition (Jones & Childers, 2002).

The operational principle of the Wheatstone bridge is grounded in the concept of a null measurement. At balance, the potential difference between the galvanometer connection points is zero, and no current flows through the galvanometer. This condition eliminates the influence of the galvanometer's internal resistance, thereby increasing measurement accuracy.

The balance equation is derived from Kirchhoff's laws. For the bridge in a balanced state:

$I_1R_1 = I_2R_2 \; and \; I_1R_3 = I_2R_4$

This relationship enables the determination of an unknown resistance when three of the resistances are known. The method's precision depends on the stability of the resistances, the sensitivity of the galvanometer, and the quality of electrical contacts.

Material selection for the conductive and contact components directly impacts measurement stability. High-conductivity metals, such as copper, minimize voltage drop at contact points, while metals with high corrosion resistance, such as aluminum when anodized, can sustain long-term reliability. Conversely, steel, while mechanically robust, introduces higher resistive losses and is more prone to oxidation, necessitating protective coatings or periodic maintenance.

The figure given below shows a variation of Wheatstone bridge, where the resistance R4 has been replaced by an unknown resistance Rx. Rx is attached to the sensing arm between the points BD, and R3 has been adjusted to give the Wheatstone Bridge its balanced condition.

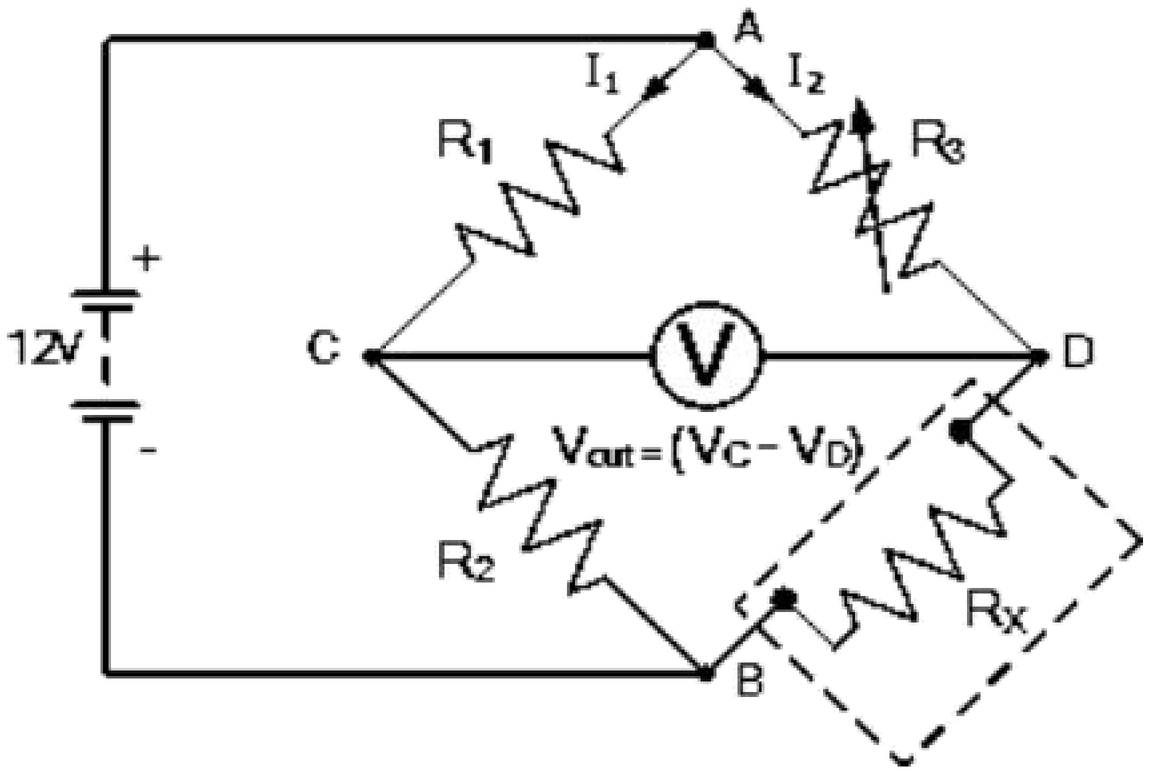


Figure 2.1. Variation of the Wheatstone Bridge.

The circuit is expected to bring zero output on the galvanometer as per the Wheatstone Bridge principle.

Thus, when the bridge is balanced, the resistances on the circuit can be indicated as equation 2.2

The Wheatstone bridge balance equation for unknown resistance R_x. Here, the values of resistors R_1 and R_2 are known or preset.

It can be calculated as shown below:

$$V_{OUT} = \left(V_C - V_D\right) = \left(V_{R2} - V_{R4}\right) = 0$$

$$R_C = \frac{R_2}{R_1+R_2} \quad \text{and} \quad R_D = \frac{R_4}{R_3+R_4}$$

$$\text{At Balance: } R_C = R_D \quad \text{So, } \frac{R_2}{R_1+R_2} = \frac{R_4}{R_3+R_4}$$

$$\therefore\ R_2\left(R_3+R_4\right) = R_4\left(R_1+R_2\right)$$

$$R_2R_3 + \cancel{R_2R_4} = R_1R_4 + \cancel{R_2R_4}$$

$$\therefore\ R_4 = \frac{R_2R_3}{R_1} = R_X$$

(2.3)

2.4 CONCEPT OF NULL DETECTION IN ELECTRICAL CIRCUIT

Null detection is a fundamental technique used in electrical measurement systems, particularly in bridge circuits such as the Wheatstone bridge and Meter Bridge. The principle is based on detecting a condition in a circuit where the measured quantity, typically current or voltage, drops to zero. This condition is referred to as a “null” point. When this occurs, it signifies a state of balance in the circuit, allowing highly accurate measurements to be made without the influence of external factors like internal resistance or voltage fluctuations.

In a typical meter bridge setup, the galvanometer is the instrument responsible for null detection. A galvanometer is a highly sensitive device that responds to the slightest current passing through it by showing a deflection on its scale. When the circuit is unbalanced, current flows through the galvanometer, resulting in deflection. As the jockey is moved along the bridge wire, the resistance on either side of the bridge changes. When the resistance ratios balance perfectly with the known and unknown resistors, the galvanometer shows no deflection this is the null point. At this moment, the potential difference between the two points connected to the galvanometer is zero.

One major advantage of null detection is that it allows measurements to be made without drawing current through the unknown component. This avoids any potential heating or distortion due to current flow, thereby preserving the integrity of the unknown resistance. As a result, null detection methods are considered non-invasive and are preferred in situations requiring high accuracy.

Another strength of null detection methods is that they are independent of the internal resistance of the measuring instrument. In direct measurement techniques, the reading can be affected by the resistance of the voltmeter or ammeter used. In contrast, at the null point in a bridge circuit, no current flows through the galvanometer, and therefore its internal resistance becomes irrelevant. This leads to measurements that are more precise and reliable.

From an educational perspective, null detection also introduces students to the concept of balance in electrical circuits. It emphasizes the importance of symmetry and proportionality in achieving equilibrium, which is a foundational principle in both physics and electrical engineering. Understanding how to detect a null point helps students and engineers appreciate how bridge circuits work and why they are such powerful tools in instrumentation and metrology.

In addition to the meter bridge, null detection plays a crucial role in potentiometers, capacitance bridges, and inductance bridges, where similar balance conditions are sought to determine unknown quantities. In more advanced instrumentation systems, null detection is automated using digital circuitry, enabling extremely precise calibration in devices like digital multimeters, oscilloscopes, and impedance analyzers.

Despite its many advantages, null detection does have limitations. It requires a highly sensitive detection instrument, such as a galvanometer, which may not always be readily available in low-resource environments. Furthermore, achieving a precise null point can be time-consuming in practice, especially when manual adjustments are involved. Nonetheless, the trade-off between time and accuracy usually justifies the use of null detection techniques in high-precision applications.

2.5 Historical Development of the Meter Bridge

The meter bridge is a refined adaptation of the Wheatstone bridge, a device first developed in the 19th century for accurate resistance measurement. Although commonly attributed to Sir Charles Wheatstone, the underlying principle was initially formulated by Samuel Hunter Christie in 1833. Wheatstone's contributions in 1843 involved popularizing the method and demonstrating its practical applications, which cemented his association with the instrument in historical literature (Maxwell, 1892).

The original Wheatstone bridge employed fixed resistors arranged in a diamond-shaped network to compare an unknown resistance with known standards. Its success in laboratory and telegraphy applications prompted further innovation, leading to the development of sliding contact variants that could accommodate continuous adjustments in resistance ratios. This advancement laid the groundwork for the meter bridge, in which a one-meter-long uniform resistance wire replaces one arm of the Wheatstone bridge.

The meter bridge gained prominence in educational institutions during the late 19th and early 20th centuries as an instructional tool for demonstrating Ohm's law, the concept of potential difference, and the principles of resistive networks. Early versions of the device utilized brass or copper plates as contact terminals, chosen for their favorable electrical conductivity and ease of fabrication (Kohlrausch, 1876). With time, innovations in materials science expanded the selection of plate materials to include aluminum and stainless steel, primarily to address issues of corrosion and cost.

Industrial research in the mid-20th century focused on refining contact stability and minimizing parasitic resistance at junctions between the wire and the plates. Studies by Townsend (1954) and later by Robertson and Hill (1971) introduced techniques for precision lapping of contact surfaces and standardized methods for mounting the resistance wire under uniform tension. These innovations greatly improved measurement repeatability, making the meter bridge suitable for both educational and industrial metrology applications.

In contemporary practice, meter bridges remain indispensable in undergraduate physics laboratories, where they are used to reinforce theoretical concepts through hands-on experimentation. Moreover, research laboratories employ customized meter bridge setups for specialized resistance measurements, particularly in material science studies involving constantan, manganin, and nichrome wires. The ongoing exploration of alternative plate materials, such as aluminum and stainless steel, reflects a broader trend towards cost-effective and durable instrumentation in developing countries where laboratory budgets may be limited.

The meter bridge, also known as the slide-wire bridge, is a practical adaptation of the Wheatstone bridge principle. It substitutes one pair of resistances with a uniform resistance wire, typically one meter in length, mounted on a rigid base. The wire is usually made from constantan, chosen for its negligible temperature coefficient of resistance, thereby ensuring stability during measurement.

In the meter bridge, the balance equation is expressed as:

$$\frac{R_x}{R_s} = \frac{l_1}{l_2} \qquad (2.4)$$

Where R_x is the unknown resistance, R_s is the standard resistance, and l_1 and l_2 are the lengths of wire on either side of the jockey contact at the balance point.

Historically, meter bridges were constructed using wooden or Bakelite bases with brass or copper contact strips. As laboratory practice evolved, the need for more durable and corrosion-resistant designs encouraged experimentation with alternative metals for the contact plates. Aluminum emerged as a lightweight, corrosion-resistant option; steel offered mechanical strength and resistance to deformation; copper remained the benchmark for electrical conductivity, though it required periodic cleaning to remove oxidation layers.

The choice of plate material affects the accuracy of measurements primarily through changes in contact resistance, surface oxidation behavior, and mechanical wear over time. This study examines these factors in the context of fabricating meter bridges from aluminum, steel, and copper plates.

The meter bridge, also referred to as a slide-wire bridge, is a linear adaptation of the Wheatstone bridge principle designed for laboratory measurement of resistance values, typically in the range of a few ohms to several tens of ohms. In this design, one arm of the bridge consists of a uniform resistive wire, often made from constantan or manganin, stretched along a calibrated one-meter scale. The variable arm is adjusted by moving a contact jockey along the wire, changing the length ratio until a balanced condition is achieved.

The governing equation for the meter bridge can be expressed as:

$$R_x = \frac{L}{100-L} \cdot R \qquad (2.5)$$

Where

R_x is unknown resistance

R is the known resistance in the other arm of the bridge

L is the length (in centimeters) of the wire to the balancing point.

This configuration allows for straightforward measurement of unknown resistances by direct proportionality of wire length to resistance, provided the wire is of uniform cross-section and resistivity (Bleaney & Bleaney, 2013).

2.6 Constantan Wire and Its Properties

Constantan is an alloy typically consisting of approximately 55% copper and 45% nickel, engineered to possess a nearly constant electrical resistivity across a wide temperature range (Bleaney & Bleaney, 2013).

This property ensures that the resistance of constantan remains effectively stable over a broad range of operating temperatures, a feature that is critical for precision measurement instruments such as the meter bridge.

The resistivity of constantan is typically about $4.9\times10^{-7}\Omega$m, remains stable between 50° C and 200° C, which makes it ideal for precision resistance measurements. This temperature stability mitigates the error caused by resistive drift, a common problem in materials with high temperature coefficients of resistance. While its resistivity is significantly higher than that of pure copper, it is advantageous in instruments requiring manageable resistance values over short lengths of wire. The negligible temperature coefficient, which is close to zero in the operational range of laboratory experiments, prevents measurement errors that would otherwise arise from ambient temperature fluctuations.

Moreover, constantan exhibits excellent ductility, allowing it to be drawn into thin, uniform wires without significant mechanical defects. In the context of a meter bridge, the uniformity of cross-sectional area is critical because the length-to-resistance relationship assumes a homogeneous conductor. Deviations in wire diameter or alloy composition can lead to localized resistance variations, thereby reducing measurement precision (Callister & Rethwisch, 2018).

The corrosion resistance of constantan, though moderate compared to noble metals, is sufficient for indoor laboratory use, provided that the wire is not exposed to aggressive chemical environments. When integrated into a meter bridge, constantan ensures that resistive readings remain reproducible over prolonged periods of experimental use.

In addition to its thermal stability, constantan exhibits good mechanical strength, resistance to oxidation, and ease of soldering, all of which contribute to its long service life in educational and industrial measurement devices. For the meter bridge, the uniformity of resistivity along the entire length of the wire is of paramount importance. Any variations, whether due to manufacturing defects or wear, can introduce systematic errors in the length-to-resistance proportionality used for measurement.

Given its stable properties, constantan is almost universally preferred for the slide wire in meter bridge constructions, regardless of the materials chosen for the contact plates.

2.7 Material Selection for Meter Bridge Construction

The choice of materials for the structural and conductive components of a meter bridge is a critical factor in determining its measurement accuracy, longevity, and operational reliability. For the present study, aluminum, steel, and copper plates were selected as comparative materials for the bridge's terminal and structural components. Each of these metals possesses distinct mechanical, electrical, and thermal properties, influencing the performance of the meter bridge in different ways.

The choice of material for the contact plates of a meter bridge is not arbitrary; it requires a balance of electrical, mechanical, and environmental considerations. The main factors influencing selection include:

1. **Electrical Conductivity (σ)**: Higher conductivity reduces contact resistance and ensures minimal voltage drop at the interface between the wire and the plates.

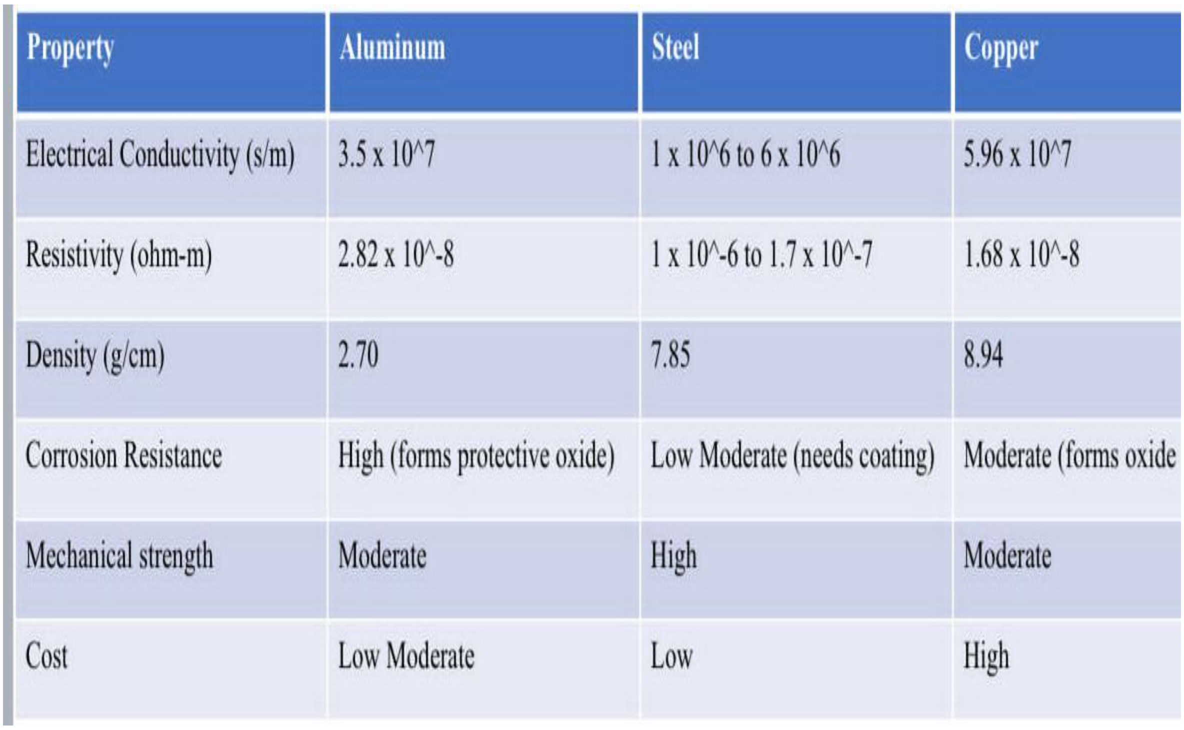
2. **Corrosion Resistance**: Oxidation or corrosion increases surface resistance and can lead to inconsistent readings over time.

3. **Mechanical Durability**: The plates must withstand repeated contact from the jockey without deformation.

4. **Cost and Availability**: Material costs and local availability determine the practicality of construction, especially for educational institutions in resource-limited settings.

The three materials under consideration in this study: aluminum, steel, and copper, differ significantly in these respects. Their key physical and electrical properties are summarized in Table 2.1.

Table 2.1: Physical and Electrical Properties of Aluminum, Steel, and Copper (Ashby 2011)



Property	Aluminum	Steel	Copper
Electrical Conductivity (s/m)	3.5 x 10^7	1 x 10^6 to 6 x 10^6	5.96 x 10^7
Resistivity (ohm-m)	2.82 x 10^-8	1 x 10^-6 to 1.7 x 10^-7	1.68 x 10^-8
Density (g/cm)	2.70	7.85	8.94
Corrosion Resistance	High (forms protective oxide)	Low Moderate (needs coating)	Moderate (forms oxide
Mechanical strength	Moderate	High	Moderate
Cost	Low Moderate	Low	High

This comparison illustrates that while copper excels in conductivity, it is more costly and moderately susceptible to oxidation. Aluminum offers a good balance of conductivity, corrosion resistance, and weight, whereas steel priorities mechanical durability but at the expense of electrical performance.

2.8 Design Principles of a Meter Bridge

The operational framework of a meter bridge is grounded in the concept of potential division along a uniform resistive wire. When a direct current source is applied across the ends of the wire, the potential difference is distributed proportionally to the length, assuming uniform resistivity and cross-sectional area. The sliding contact (jockey) allows the experimenter to select a specific length ratio that balances the Wheatstone bridge configuration.

For optimal performance, the design must satisfy several engineering and metrological requirements:

1. **Uniformity of Resistive Wire** – The resistance per unit length must be constant to ensure linear proportionality between length and resistance.
2. **Low-Resistance Contacts** – Terminal plates and connecting leads should introduce minimal additional resistance to avoid altering the effective arm ratios.
3. **Mechanical Stability** – The frame must resist deformation under handling to maintain accurate length calibration.
4. **Minimal Thermal Gradient** – Non-uniform heating along the wire can produce resistance variations, leading to systematic measurement errors.These design principles apply equally to meter bridges fabricated with aluminum, steel, or copper plates, although the choice of plate material influences factors such as contact resistance and structural stability.

2.9 Application of Meter Bridge

The meter bridge is a versatile instrument used in both academic and practical applications. Below are some of its major uses:

1. Measurement of Unknown Resistance: This is the most common application of a meter bridge. It allows accurate calculation of an unknown resistance by using a known resistance and balancing lengths on a bridge wire.

2. Verification of Ohm's Law: The setup can be adapted to verify Ohm's Law in laboratory conditions by comparing the proportional relationships between voltage, current, and resistance.
3. Comparative Studies: It is used in comparing the resistances of various wire materials, such as copper, aluminum, steel, and constantan, which is important for selecting suitable materials for electrical circuits.

4. Calibration: Meter bridges can be used to calibrate other resistance-measuring instruments by comparing their readings with the results obtained from the bridge.

5. Educational Demonstrations: Meter bridges are widely used in secondary schools and universities for demonstrating basic electrical principles such as current division, resistance, and balanced bridge circuits.

6. Industrial Testing: In some industries, meter bridges are used for testing electrical properties of wires and cables under controlled conditions.

2.10 Factors Affecting Measurement Accuracy in Meter Bridges

The precision of resistance measurement in a meter bridge is contingent upon both electrical and mechanical factors. Notable influences include:

- **Contact Resistance**: The resistance at the junction between the resistive wire and terminal plates can distort the effective resistance ratio, particularly in low-resistance measurements.

- **Parallax Error**: Misalignment of the observer's eye with the scale markings during balance point reading introduces systematic errors.

- **Thermal Expansion**: Both the resistive wire and the supporting frame undergo dimensional changes with temperature variations, potentially altering the length-to-resistance ratio.

- **Material Oxidation**: Oxidation on the terminal plate surfaces can increase contact resistance; copper is especially susceptible without protective coatings.

- **Strain Effects**: Mechanical tension or relaxation in the resistive wire can modify its cross-sectional area and consequently its resistance.

While calibration procedures can mitigate some of these errors, the inherent properties of the chosen plate material directly influence the extent to which these factors impact measurements.

2.11 Aluminum Plate Meter Bridge

Aluminum is a lightweight, corrosion-resistant metal with a relatively high electrical conductivity (approximately 37.7 × 10^6 S/m), making it an attractive choice for contact plates in meter bridge fabrication. Its low density makes it advantageous for portable laboratory apparatus, while its corrosion resistance ensures durability under varied environmental conditions.

Aluminum has historically been considered an attractive alternative to copper in electrical apparatus due to its relatively high electrical conductivity, low density, and favorable cost-to-performance ratio. While its conductivity (approximately 61% that of copper) is lower, the reduced mass of aluminum plates can contribute to the portability and ease of handling of a meter bridge in educational environments (Ashby, 2011).

At approximately 61% IACS, its conductivity is lower than that of copper but substantially higher than that of steel. The principal advantage of aluminum lies in its excellent corrosion resistance, achieved through the formation of a thin, stable oxide layer (aluminum oxide) that protects the underlying metal from further oxidation. However, aluminum has a lower conductivity compared to copper, which may introduce minor resistive losses at contact points if not properly designed (Callister & Rethwisch, 2018).

In the context of meter bridge construction, Zhang et al. (2019) evaluated the performance of aluminum contact plates in a laboratory-built prototype. The study revealed that, following an initial stabilization period, the contact resistance achieved a consistent value of approximately 0.05 Ω, a level that was considered satisfactory for pedagogical experiments in resistance measurement. This performance was deemed comparable to copper-based designs, provided that appropriate maintenance of the sliding contact interface was conducted.

From a materials science perspective, Callister and Rethwisch (2018) note that aluminum rapidly develops a thin, adherent oxide film upon exposure to air. While this oxide layer provides corrosion protection, it is electrically insulating, which necessitates periodic removal or the use of conductive lubricants to maintain optimal contact performance in a meter bridge. In educational settings where equipment may be handled by multiple users with varying levels of care, this maintenance requirement becomes a critical operational consideration.

Kumar and Sharma (2017) conducted an economic assessment of aluminum plates for use in low-cost educational meter bridges. Their results indicated that replacing copper plates with aluminum reduced total fabrication costs by approximately 18%, with negligible losses in accuracy under controlled laboratory conditions. The authors concluded that aluminum was a viable cost-reduction strategy for institutions seeking to expand laboratory access without compromising instructional quality.

From a measurement perspective, aluminum plates provide low and stable contact resistance when kept clean and free of contaminants. However, the naturally formed oxide layer, though protective, is non-conductive and may interfere with the reliability of electrical contacts over time. This necessitates careful maintenance, such as periodic polishing or the use of conductive greases to maintain optimal performance.

Mechanically, aluminum is sufficiently durable for laboratory use, although its relatively low hardness compared to steel means that it is more prone to surface scratching under repeated use of the jockey. In practice, the scratches are usually superficial and have minimal effect on performance unless they accumulate to the extent that they alter the contact geometry.

Therefore, aluminum plates, when properly maintained, can deliver reliable measurement performance at reduced cost and mass. However, their long-term performance remains contingent on preventing excessive oxide build-up and ensuring consistent contact surface cleanliness.

2.12 Steel Plate Meter Bridge

Steel is an alloy predominantly composed of iron with varying amounts of carbon and other alloying elements, it is valued in engineering applications for its mechanical strength and resistance to deformation. Steel offers superior mechanical strength and rigidity, which is beneficial for structural stability in precision instruments. However, its electrical conductivity (approximately 6×10^6 S/m) is significantly lower than that of aluminum or copper. This lower conductivity can result in higher contact resistance, potentially affecting measurement precision unless mitigated through design strategies such as plated terminals or high-pressure contacts (Ashby, 2011).

These properties ensure that steel plates can endure repeated mechanical stresses without bending or significant wear. However, steel's electrical conductivity is markedly lower than that of both aluminum and copper, typically ranging between 3% and 10% IACS depending on composition. The higher resistivity introduces additional contact resistance, which may slightly reduce the sensitivity of the meter bridge, particularly when measuring very small resistance values.

Steel, particularly mild steel, is not traditionally associated with high-precision electrical instrumentation due to its significantly lower electrical conductivity compared to copper and aluminum. However, its high mechanical strength and wear resistance have made it a viable choice in applications where robustness is prioritized over absolute measurement accuracy (White & Smythe, 2015).

In their investigation of mild steel plates in sliding-wire devices, Zheng and Xu (2019) reported that untreated mild steel exhibited an average contact resistance of approximately 0.2 Ω, substantially higher than copper or aluminum equivalents. This elevated resistance can introduce measurable errors in low-resistance experiments. However, when nickel-plated, the steel plates demonstrated a 40% reduction in contact resistance, suggesting that surface treatment can significantly improve their electrical performance.

Okafor et al. (2016) performed a comparative analysis of steel and copper contact plates in secondary school meter bridges. While steel exhibited a slightly reduced measurement accuracy, it demonstrated superior resistance to deformation and wear, resulting in a 25% longer service life under frequent use. The study highlighted the importance of balancing mechanical and electrical performance when selecting contact materials.

Similarly, Nwachukwu and Ali (2018) surveyed Nigerian secondary schools and found that steel plates were often preferred for their durability and affordability, despite slightly higher measurement errors. Their findings underscore the practical reality that, in resource-constrained educational systems, the lower cost and extended durability of steel may outweigh the modest loss in measurement precision.

A significant drawback of steel is its susceptibility to corrosion in the form of rust when exposed to moisture and oxygen. Rust formation not only degrades the mechanical surface but also significantly increases electrical contact resistance. For this reason, steel plates used in meter bridges must often be plated with a more conductive and corrosion-resistant metal, such as nickel or chromium, or coated with anti-corrosive layers.

The issue of corrosion is a persistent challenge for steel components in meter bridges. White and Smythe (2015) observed that rust formation led to gradual increases in contact resistance, particularly in humid laboratory environments. They recommended the use of protective coatings or stainless-steel alloys to maintain stability over extended usage.

Nevertheless, steel remains a practical choice in environments where mechanical durability outweighs the need for the absolute lowest contact resistance, especially in educational laboratories where physical damage from handling is a concern.

2.13 Copper Plate Meter Bridge

Copper is the benchmark for electrical conductivity, defined as 100% IACS, and has a correspondingly low resistivity of 1.68μΩcm. This exceptional conductivity ensures minimal voltage drop across contact interfaces, maximizing the accuracy of resistance measurements in a meter bridge.

Copper is widely recognized for its excellent electrical conductivity (58×10^6 S/m), second only to silver among commonly used metals. Its superior conductivity minimizes resistive losses at connection points, thereby enhancing measurement accuracy. Nevertheless, copper is prone to oxidation over time, necessitating periodic cleaning or protective coatings to maintain consistent electrical contact (Jones & Childers, 2002).

These material-specific differences suggest that the meter bridge's overall performance is not solely dependent on its resistive wire but is also significantly influenced by the properties of its terminal plates and structural framework.

Copper remains the benchmark material for meter bridge contact plates due to its high electrical conductivity (second only to silver) and stability under most laboratory conditions. Its low contact resistance is particularly advantageous for precision measurement of small resistances (Singh et al., 2020).

Singh et al. (2020) measured contact resistances below 0.02 Ω in copper plates under standard laboratory conditions, making them the most suitable for high-accuracy meter bridge experiments.

However, oxidation was found to increase resistance by approximately 15% over a two-week period without protective measures.

Adekunle and Ojo (2017) conducted a six-month study on the performance of polished copper plates in Nigerian educational laboratories. The plates maintained accuracy within ±0.5% during the test period, although the authors recommended silver plating as a long-term measure to prevent oxidation-related performance degradation.

Patel and Desai (2014) compared copper and aluminum plates in resistance measurement experiments, reporting that copper plates yielded approximately 8% higher accuracy in low-resistance measurements. They attributed this advantage to copper's lower contact resistance and reduced susceptibility to contact instability.

Martinez et al. (2019) explored the effects of various surface treatments on copper plates. Gold plating was found to virtually eliminate resistance drift over a one-year period, albeit at a significantly increased material cost. This suggests that treated copper plates could offer both long-term stability and high accuracy, though the financial implications may limit their widespread adoption in educational settings.

Mechanically, copper possesses moderate strength and is more ductile than both steel and aluminum. While this ductility aids in manufacturing and shaping the plates, it also means that copper plates can deform slightly under repeated mechanical pressure, which may eventually alter contact consistency.

In terms of corrosion behavior, copper develops a thin oxide layer (cuprous oxide, Cu_2O) when exposed to air, which can progress to a green patina (basic copper carbonate) under prolonged exposure to moisture and carbon dioxide. Although these layers are relatively stable, they are less conductive than pure copper and can increase contact resistance over time. Regular cleaning of the contact surfaces can mitigate this effect.

Copper’s primary disadvantage is cost, as it is significantly more expensive than both aluminum and steel. This can limit its use in large-scale or budget-constrained educational applications despite its superior electrical properties.

2.14 Material Conductivity Considerations

The electrical conductivity (σ) of a material is inversely proportional to its resistivity (ρ), given by:

$$\sigma = \frac{1}{\rho} \tag{2.6}$$

The following table summarizes the approximate resistivity and conductivity values of copper, aluminum, and steel:

Material	Resistivity (ρ) × 10^{-8} Ω·m	Conductivity (σ) × 10^{6} S/m
Copper	1.68	59.6
Aluminum	2.82	35.5
Steel	10.0 – 15.0	6.0 – 10.0

The high conductivity of copper makes it the optimal choice for minimizing resistive losses. Aluminum, while slightly less conductive, offers advantages in weight and corrosion resistance under certain conditions. Steel's lower conductivity makes it less ideal for precision electrical measurements unless treated or alloyed for improved performance.

2.15 Comparative Studies on Terminal Plate Materials

Empirical comparisons of aluminum, steel, and copper plates in precision measurement devices have shown that conductivity differences significantly affect contact resistance (Ashby, 2011). Copper plates, due to their high conductivity, generally provide the lowest contact resistance, thereby maximizing measurement precision. However, copper's tendency to oxidize necessitates either regular maintenance or the application of anti-oxidation coatings.

Aluminum plates, while offering lower mass and excellent corrosion resistance, have a slightly higher contact resistance than copper. In practice, the difference is negligible for most educational laboratory applications but may become relevant in high-precision metrology.

Steel plates offer the greatest structural rigidity but exhibit the highest contact resistance among the three materials considered. This property may limit their utility in applications requiring sub-ohm measurement accuracy unless special contact surface treatments are applied.

These comparative observations underscore that the choice of plate material involves trade-offs between conductivity, durability, corrosion resistance, and structural integrity.

2.16 Thermal and Environmental Effects on Meter Bridge Performance

Environmental conditions play a critical role in determining the long-term stability of meter bridge measurements. Thermal expansion coefficients vary among the materials in question copper ($16.5\times10^{-6}/^{\circ}$ C), aluminum ($23\times10^{-6}/^{\circ}$ C), and steel ($12\times10^{-6}/^{\circ}$ C) leading to differential expansion between the resistive wire and the supporting frame or terminal plates. Such mismatches can alter mechanical tension in the wire and shift balance points subtly over time (Callister & Rethwisch, 2018).

Humidity and airborne contaminants can accelerate surface oxidation, particularly in copper, while aluminum naturally forms a stable oxide layer that protects against further degradation. Steel, unless stainless, is prone to rust under humid conditions, which can significantly degrade contact quality. Laboratory environments that maintain moderate temperature and low humidity are therefore preferable for preserving meter bridge performance.

2.17 Advances in Material Engineering for Precision Instruments

Recent advancements in material engineering have facilitated the improvement of contact and structural components in resistance measurement instruments such as meter bridges. Surface treatment technologies, including electroplating with gold, silver, or nickel, have been applied to copper and steel plates to mitigate oxidation while maintaining high conductivity (Singh et al., 2020). In copper plates, silver plating can significantly enhance corrosion resistance without substantially affecting contact resistance values.

For aluminum, anodization creates a uniform oxide layer that not only increases corrosion resistance but also improves surface hardness. However, anodization may slightly increase surface resistivity;

therefore, a balance between protection and electrical performance must be considered. Steel plates, particularly mild steel, can benefit from nickel or chromium plating to resist rust and preserve mechanical integrity over extended use.

Additionally, composite materials combining metallic plates with conductive polymers have been explored for educational laboratory devices, aiming to reduce weight while maintaining acceptable conductivity. Although not yet widespread in meter bridge fabrication, these approaches suggest future directions for improving durability and performance in harsh environments.

2.18 Historical Evolution of Meter Bridge Designs

The meter bridge, as a derivative of the Wheatstone bridge, emerged in the late nineteenth century as a practical educational tool for demonstrating electrical resistance measurement principles. The earliest designs featured brass fittings and hardwood bases, with the resistive wire often made of manganin or constantan (Thompson, 1891). Brass was preferred for its corrosion resistance and machinability, although it introduced slightly higher contact resistance compared to copper.

In the mid-twentieth century, aluminum began replacing brass in many laboratory instruments due to its lower cost, lighter weight, and ease of fabrication. Steel components were introduced primarily for their robustness in industrial training environments where mechanical wear was a concern.

In contemporary academic settings, meter bridges are increasingly produced with hybrid materials for example, aluminum frames with copper terminal plates to balance mechanical stability and electrical performance. The continued adaptation of materials reflects a broader trend in metrology towards optimizing both the functional and economic aspects of instrument design.

2.19 Research Gap

2.19.1 Gaps in Aluminum-Based Meter Bridge Studies

Previous studies on aluminum plates, such as those by Ashby (2011), Callister and Rethwisch (2018), and Zhang et al. (2019), have emphasized aluminum's attractive balance of low weight, cost-effectiveness, and resistance to corrosion. Kumar and Sharma (2017) further demonstrated its applicability in low-budget educational settings, where aluminum meter bridges are often introduced as alternatives to more expensive copper-based models.

However, despite these contributions by the names mentioned above, the studies present certain limitations. A recurring issue is the natural formation of aluminum oxide on the surface, which increases contact resistance and may compromise measurement accuracy. While the oxide layer provides corrosion resistance, its insulating effect creates inconsistencies during prolonged laboratory use. None of the cited works conducted a systematic long-term study on how oxide accumulation influences performance after several months or years of repeated handling by students. Instead, their conclusions were often based on short-term laboratory demonstrations.

Furthermore, most investigations into aluminum were carried out in controlled environments, with minimal attention to real-world laboratory conditions such as fluctuating humidity, poor maintenance, and repeated mechanical stresses. This oversight leaves uncertainty about whether aluminum-based bridges can consistently provide accuracy comparable to copper under practical conditions. As a result, while aluminum has been acknowledged as a low-cost substitute, there remains insufficient empirical evidence to establish its long-term reliability and pedagogical suitability.

2.19.2 Gaps in Steel-Based Meter Bridge Studies

Steel, as highlighted by Ashby (2011), White and Smythe (2015), and Zheng and Xu (2019), has often been presented as a durable material with remarkable mechanical strength, making it appealing in laboratories where equipment longevity is a concern. Okafor et al. (2016) and Nwachukwu and Ali (2018) confirmed that steel-based meter bridges tend to last longer in student laboratories where physical mishandling is common.

Despite its durability and mechanical strength, the principal drawback lies in steel's relatively poor electrical conductivity compared to aluminum and copper. This limitation translates into higher contact resistance, thereby reducing the sensitivity and precision of resistance measurements. While studies such as those of Okafor et al. (2016) recognized this limitation, they did not explore interventions that could mitigate the problem, such as coating steel plates with conductive materials (e.g., nickel or chromium plating).

Moreover, corrosion remains a major concern. Unlike aluminum, steel is highly susceptible to rusting in humid environments. Yet, the reviewed literature does not provide long-term data on the impact of rust accumulation on measurement error in meter bridges. This leaves a gap in understanding whether steel's mechanical durability truly compensates for its electrical disadvantages in the context of sustained laboratory use.

Thus, while steel-based meter bridges are recognized for their robustness, the lack of comprehensive durability testing under corrosive conditions and the absence of studies exploring surface treatment solutions create significant knowledge gaps.

2.19.3 Gaps in Copper-Based Meter Bridge Studies

Copper remains the most widely accepted material for meter bridges, with works by Jones and Childers (2002), Singh et al. (2020), and Adekunle and Ojo (2017) confirming its superior electrical conductivity and low contact resistance. Patel and Desai (2014) reinforced copper's status as the benchmark material by demonstrating its unmatched accuracy in controlled laboratory environments.

Martinez et al. (2019) further showed that surface treatments like gold plating can reduce resistance drift and improve long-term stability.

Despite these findings, copper-based meter bridges face notable challenges that have not been adequately addressed in literature. The first is copper is expensive, limiting its use in schools and universities operating with restricted budgets. Although several researchers acknowledge this barrier, few studies provide detailed cost-benefit analyses that weigh copper's performance advantage against its financial burden in educational contexts.

Additionally, copper is susceptible to oxidation (tarnishing) over time. While Martinez et al. (2019) touched on surface treatments, very little research has been conducted on how untreated copper plates perform after long-term student use in laboratories with suboptimal maintenance. Most of the studies available focus on short-term performance under ideal laboratory conditions, leaving uncertainty about the sustainability of copper-based meter bridges in real-world educational settings.

In summary, while copper offers accuracy and sensitivity, research has not fully addressed how cost constraints and oxidation challenges affect its long-term practicality for large-scale adoption in developing regions.

2.19.4 Cross-Cutting Limitations Across Aluminum, Steel, and Copper Studies

A significant observation from the reviewed works is that most investigations were conducted in isolation, focusing on one material type at a time. This fragmented approach makes it difficult to draw direct comparisons between aluminum, steel, and copper under uniform experimental conditions. For instance, studies on aluminum emphasize cost-effectiveness and corrosion resistance, those on steel highlight durability at the expense of conductivity, and those on copper underline precision with little consideration of cost and oxidation.

The lack of standardized testing frameworks across studies means there is no consensus on which material provides the optimal balance of cost, accuracy, durability, and maintenance requirements for educational laboratories. Additionally, very few researchers integrated economic and mechanical performance into the same evaluation framework. As a result, policy decisions on material adoption for laboratory equipment often rely on assumptions rather than comparative empirical evidence.

Another cross-cutting limitation is the time scale of testing. Most studies assessed material performance over short durations in well-maintained laboratories, failing to capture the challenges of long-term use in typical school environments, particularly in resource-limited regions where laboratory equipment is often handled roughly and rarely replaced.

2.19.5 Research Gap Summary

From the review above, the following critical gaps are identified:

1. Aluminum studies did not adequately address the long-term impact of oxide layer formation on accuracy.
2. Steel studies emphasized durability but ignored systematic corrosion mitigation strategies and their influence on precision.
3. Copper studies confirmed accuracy but did not fully account for high cost and oxidation challenges in real-world school environments.
4. None of the reviewed works conducted a direct comparative evaluation of aluminum, steel, and copper plates fabricated and tested under identical conditions.
5. Few studies integrated economic analysis with electrical and mechanical performance in their assessment of meter bridge suitability for educational use.

2.20 Justification of the Study

The identified gaps provide a strong rationale for this research. The fabrication of meter bridges using aluminum, steel, and copper plates under uniform experimental conditions offers a rare opportunity to generate direct comparative data. Unlike previous works, this project does not treat each material in isolation but instead evaluates them side-by-side to highlight their respective strengths and weaknesses.

This is particularly justified in the context of undergraduate physics education in developing regions, where cost, durability, and maintenance are just as important as measurement accuracy. By addressing cost-effectiveness, long-term usability, and environmental durability in one study, the project directly responds to the lack of integrative research in this area.

Furthermore, this project contributes to practical pedagogy. Constructing the meter bridges locally using accessible materials allows students to not only perform experiments but also understand the engineering and design choices underlying laboratory apparatus. This aligns with the broader goal of fostering technical innovation, problem-solving skills, and contextualized learning in physics education.

CHAPTER THREE

METHODOLOGY

3.1 Theory of Operation

This chapter explains the principle behind the Wheatstone bridge, which is the foundation of the meter bridge. It also covers how the experiment was set up, the materials used, and the steps followed to build and test the meter bridge.

For this study, three different versions of the meter bridge were made, each with a different material for the terminal plates aluminum, steel, and copper. Comparing these versions helps us understand how the choice of material affects conductivity, surface resistance, durability, and ultimately the accuracy of the meter bridge.

3.2 Materials and Components

The materials were carefully and locally selected based on availability, cost, and suitability for laboratory applications.

Core Materials:

- Wooden base: The wooden base, measuring 104 cm and smoothed for uniformity, provides a sturdy, non-conductive platform to mount all the components of the meter bridge.
- Constantan wire: The main resistive element is a 1-meter length of constantan wire, chosen for its low temperature coefficient of resistance, which ensures stable measurements.
- Aluminum and Steel plates: Terminal plates made of aluminum and steel (0.12 m × 0.03 m, 2 mm thick) serve as the points of connection between the wire and the external circuit. Using different plate materials allows for a comparative study of how conductivity, surface resistance, and durability affect the meter bridge's performance.

- Meter rule: A precision-engraved 100 cm meter rule is used to measure the balance point along the wire accurately.
- Galvanometer: A highly sensitive galvanometer (~10^{-9} A) detects the null point when the bridge is balanced.
- Jockey: A spring-loaded brass jockey is used to slide along the wire and locate this balance point, providing reliable contact without damaging the wire.
- Connecting wires : Using the same material (Constantan) minimizes additional resistance effects. It is used to connect different components of the meter bridge circuit.
- Screws, nails, Evo- stick gum: Used to fix the wire and plates securely on the wooden base and also to ensure mechanical stability during measurements.
- Soldering lead: Provides firm electrical connections between the wire and terminal plates
- Power supply (Leclanche cell): A Leclanché cell providing 4 V serves as the power supply, supplying the required current safely for laboratory measurements.
- Resistance box: A resistance box containing known resistances is included for comparison with unknown resistances

Equipment Used:

- Saw, Plane,and Carpenter's tools: Used to cut and shape the wooden base and terminal plates accurately.

- Drilling machine: To creates holes for screws and wire placement with high accuracy.

- Measuring tape (length accuracy ±0.1 cm): Ensures proper measurements for positioning components and wire length.

- Soldering iron and flux: Used to solder wires securely to the plates, ensuring good electrical connections.

- Multimeter: Used for preliminary testing of wire and connection resistances to ensure proper functioning before the experiment.

3.3 Fabrication Process

The fabrication process was divided into systematic stages to ensure consistency across the three variants.

3.3.1 Preparation of the wooden base

A wooden board of length 104 cm was cut and smoothened to ensure smoothness and uniformity. Holes were drilled at predetermined points for fixing the meter rule and mounting the plates. The base provides both insulation and mechanical stability.

3.3.2 Mounting of the Meter Rule and Wire

A 100 cm meter rule was affixed centrally on the base using Evo-stick gum. The constantan wire was stretched tightly over the meter rule, anchored at both ends by the terminal plates. Uniform tension was ensured to avoid sagging, as non-uniformity could distort resistance measurements.

3.3.3 Fixing of Strips and Plates

Two sets of terminal plates (aluminum, steel,) were prepared. Each set was cut to identical dimensions (12 cm × 3 cm), polished to remove oxide/rust, and mounted on the wooden base using screws. These plates served as end contacts for the wire and as terminals for circuit connection.

The Aluminum plates which are of lightweight, corrosion-resistant, required periodic polishing due to oxide formation.Steel plates: mechanically strong but prone to rust; some were nickel-plated to improve conductivity.

3.3.4 Mounting of Terminals

Each end of the constantan wire was carefully soldered to its aluminum, steel, or copper plate. Before soldering, the plates were cleaned to remove dust, grease, and oxide layers, which helps minimize extra resistance at the contact points.

The wire ends were held securely with clamps during soldering to create strong, reliable connections, taking care not to overheat the wire and alter its resistance. After soldering, the joints were left to cool naturally to maintain stability.

Connections for the galvanometer and jockey were made at specific points on the plates. The jockey, with its spring-loaded brass tip, slides along the wire to locate the balance point while maintaining good contact without damaging the wire. Finally, all connections were checked with a multimeter to confirm they were secure and had low resistance, ensuring the meter bridge provides accurate and dependable readings during the experiment.

Plate 1; Consist of a wooden base, aluminum plates, meter rule, constantan wire and six black connectors.

3.3.5 Connection of electrical components

The electrical components were carefully connected. The galvanometer was linked to the terminal plates using flexible wires, allowing it to detect the balance point accurately without restricting movement. A standard resistor was incorporated into the circuit to serve as the known resistance for comparison with the unknown resistance. The jockey, with its spring-loaded brass tip, was connected to slide along the wire and identify the point where the galvanometer reads zero, indicating balance. The power supply, a 4V Leclanché cell, provided the necessary current for the circuit in a safe and controlled manner.

Before beginning the experiment, all connections were tested with a multimeter to ensure the wires were continuous, the terminals were properly connected, and there were no loose or faulty connections. This careful setup ensured that the meter bridge functioned reliably and provided accurate resistance measurements.

3.4 Assembly of Components

The final setup consisted of:

- The wooden meter bridge base (with wire and ruler fixed).
- Terminal plates (aluminum/steel/copper variants).
- Constantan wire stretched taut.
- Jockey for sliding contacts.
- Galvanometer for null detection.
- Standard resistors and battery source for testing.

The final meter bridge setup was assembled by carefully connecting all the components to form a complete and functional circuit. The wooden base, with the constantan wire stretched tightly across it and the meter rule fixed in place, served as the foundation. The terminal plates made of aluminum, steel, or copper were securely attached at each end of the wire.The galvanometer was connected to the terminals using flexible wires, allowing it to detect the balance point accurately without restricting movement. The jockey, with its spring-loaded brass tip, was positioned to slide along the wire, making smooth contact to locate the null point. Standard resistors were incorporated into the circuit to act as known resistances for comparison, while the battery provided a safe and steady current to the system.All connections were carefully checked for continuity and stability using a multimeter before performing any measurements. This careful assembly ensured that the meter bridge operated smoothly, providing reliable and accurate readings for the experiment.

Plate 2: The final setup of Meter bridge

The practical arrangement of the meter bridge is based on the Wheatstone bridge principle. In this form, one of the branches, ADC consists of a wire of uniform cross section and of length 100cm. The point D is located by a sliding contact. The unknown resistance X is placed in one arm of the other branch, the remaining arm containing the known resistance R which usually is in the from of a resistance box as shown in the figure below,

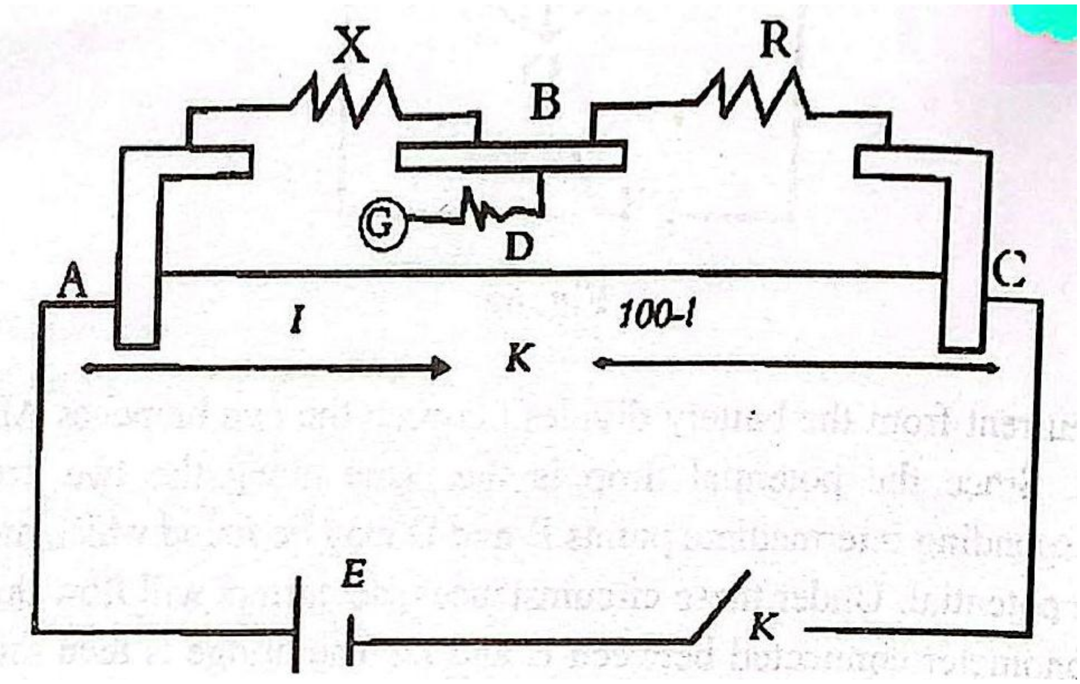


Figure 3.1: practical arrangement of the meter bridge

The condition is given by:

$$\frac{X}{R} = \frac{\text{Resistance of } AD}{Resistance\ of\ DC} \qquad 3.1$$

But since the wire is uniform, its resistances is directly proportional to its length. Thus,

$$\frac{X}{R} = \frac{L}{(100-L)} \qquad 3.2$$

3.4.1 Preliminary Testing

- A known resistor (1 Ω) was connected, and the balance point determined.
- Measurements were repeated at multiple points to confirm linearity.
- Each meter bridge (aluminum, steel, copper) underwent identical testing.

3.4.2 Comparative Performance Study

EXPERIMENT: Determination of an Unknown Resistance Using a Meter Bridge

Apparatus

- The unknown resistance
- A Leclanché cell
- A centre-zero galvanometer
- A galvanometer key (protector)
- A resistance box
- A sliding contact or jockey
- A meter bridge

To measure and compare the resistances obtained from the different meter bridge setups, the experiment was conducted to determine an unknown resistance using the meter bridge. The apparatus used included the unknown resistance, a Leclanché cell as the power source, a centre-zero galvanometer with a protective key, a resistance box for the known resistances, a sliding contact or jockey, and the meter bridge itself.The circuit was assembled as shown in Figure 3.1, with X representing the unknown resistance. Before taking measurements, several important precautions were observed to ensure accuracy and protect the equipment:

1. The bridge wire must be uniform along its length. The jockey should touch the wire lightly to avoid damaging it or altering its resistance. If the balance point is not easily detected, the jockey can be gently cleaned with fine emery cloth, and the wire should also be cleaned and wiped to maintain consistent contact.
2. Unlike a potentiometer, the voltage source for a meter bridge does not need to be constant. A Leclanché cell is preferred because it provides adequate voltage while its

higher internal resistance limits current to a safe level, preventing damage to the galvanometer.

3. The galvanometer is delicate and can be damaged by excessive current. A high-resistance resistor is placed in series with it until a rough balance point is found.
4. The circuit key should be closed before making contact with the jockey at the sliding point to minimize deflections caused by induction effects.
5. The highest accuracy is achieved when the balance point lies near the centre of the bridge wire. Therefore, the known resistance should be selected so that the balance point occurs between 40 cm and 60 cm along the wire.

Experimental Procedure

After ensuring the circuit was correctly connected, the current was switched on. The jockey was moved gently along the bridge wire until the galvanometer showed no deflection, indicating a balance point. The length L from one end of the bridge wire to the balance point was measured and recorded.

Next, the known and unknown resistances were interchanged, and the new balance length L' was determined and recorded. Using the two balance lengths obtained, the value of the unknown resistance X was calculated using the meter bridge relation:

$$\frac{X}{R} = \frac{L}{(100-L)} \qquad 3.3$$

The mean of the two calculated values of X was then taken as the final value.

Determination of Resistivity

The resistances of the provided wires were determined by the same procedure. Their lengths were measured using a meter rule, and their diameters were measured using a micrometer screw gauge. The specific resistance (ρ) or resistivity of each wire was then calculated using:

$$\rho = \frac{RA}{L} = \frac{(R\pi d^2)}{(4l)} \qquad 3.4$$

where R is measured resistance (Ω),

d is diameter of the wire (m), and

L is length of the wire (m).

The results were tabulated, and observations were made to comment on the agreement between experimental and theoretical values.

Code Numbers of Resistance Wires

The code numbers of the resistance wires used were recorded for identification and comparison.

Note on Accuracy

The accuracy of the experiment depends primarily on the sensitivity of the galvanometer. The minimum distance through which the jockey must be moved from the balance point to produce a just-noticeable deflection of the galvanometer was determined. Suppose this minimum distance corresponds to 1 mm, and the balance point is:

$L = 42.5$ cm

Then the possible measurement error is:

$L = 42.5 \pm 0.1$ cm, $(100 - L) = 57.5 \pm 0.1$ cm

The possible percentage error is therefore:

Total possible error = 0.4%

Since X ∝ L / (100 - L), the possible error in X is also 0.4%. If X = 4.55 Ω, the true value becomes:
X = (4.55 ± 0.02) Ω.

In your own experiment, determine the minimum noticeable deflection distance of the galvanometer, calculate the corresponding error in X, and express your final result with the error included.(Practical Physics Manual(2024). Department of Physics, University of Benin, Benin city, Nigeria.)

Aluminum bridge: Observed stable contact resistance (~0.05 Ω) with occasional need for polishing.

Steel bridge: Higher initial resistance (~0.2 Ω untreated), improved with nickel plating.

3.4.3 Error Considerations

- Contact resistance due to oxidation/rust.
- Non-uniform stretching of the constantan wire.
- Parallax error in reading the meter rule.
- Thermal fluctuations affecting wire resistivity.

Mitigation strategies included frequent cleaning of plates, careful calibration, and conducting measurements at stable room temperature.

3.4.4 Justification of the Two Variants

The fabrication of the meter bridges (aluminum, steel plates) was deliberate to:

- Compare conductivity vs. durability in practical educational settings.

- Test cost-effectiveness: aluminum is cheaper, steel is durable, copper is accurate but costly.
- Address the research gap identified in Chapter Two: lack of systematic comparison under
- controlled experimental conditions.
- This methodology ensures that results obtained are not only valid but also provide practical insights for institutions making material choices for laboratory instruments.

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter presents the results obtained from the experimental investigation of the internal resistance, resistivity, and conductivity of a constantan wire using the fabricated meter bridge with three different terminal plates Aluminum, Steel, and Copper. The objective was to examine how the plate material affects the accuracy of measurements when a thick wire is used as the bridge conductor. All relevant data were collected, analyzed, and compared with the theoretical (standard) values of resistivity and conductivity for the materials to assess the performance of the fabricated device.

4.1 Experimental Results for Constantan Wire

The experimental readings obtained from the meter bridge setup using Aluminum, Steel and copper plates are represented in table 4.1 below. The table shows the known resistance connected in the circuit, the balance lengths(L_1 and L_2), the average length(L) and the total of the constantan wire used for the measurement. These readings forms the basis for determining the unknown resistance, resistivity and conductivity of the wire for each of the terminal plates.

Table 4.1 Experimental results for constantan wire

Material Plate	Diameter Of Wire (Mm)	Known Resistance (Ω)	L_1 (Cm)	L_2 (Cm)	$L=\frac{L_1 + L_2}{2}$ (Cm)	Length Of Wire (Cm)
Aluminum	0.15	2	54	43	48.5	100
Steel	0.15	2	50	53	51.5	100
Copper	0.15	2	49	43	46	100

From the table, it can be observed that the balance length (L) varied slightly for each material plate. These variations indicate the effect of terminal plate materials on the potential distribution along the bridge wire, which ultimately affects the accuracy of the resistance measurement.

4.2 Explanation of Resistance, Resistivity, and Conductivity

In order to determine the electrical properties of the constantan wire used in this experiment, a series of calculations were carried out based on the readings obtained from the meter bridge setup. These calculation include the determination of the resistance(R)of the wire, it's resistivity (ρ), and conductivity(σ). The relationships among these parameters help to describe how efficiently the wire conducts electricity and how different terminal plates materials influence its performance. The formulas applied are standard expressions in electrical measurements and are explained below before the computation of each parameter.

(a) Resistance(R): It is a measure of the opposition to the flow of current in an electrical circuit. It depends on the material's nature, length and cross sectional area.

Formula:

$$R = \rho L/A \qquad 4.1$$

Where:

- R is Resistance (Ω)
- ρ is Resistivity of the material (Ωm)
- L is Length of the conductor (m)
- A is Cross-sectional area (m^2)

In the meter bridge, resistance is calculated from the bridge balance condition using known and unknown resistances.

(b) Resistivity (ρ): Resistivity is a material property that quantifies how strongly it resists the flow of electric current. It is independent of the shape or size of the material.

Formula:

$$\rho = \frac{RA}{l} \qquad 4.2$$

Where:

- P is Resistivity (Ωm)
- R is Measured resistance (Ω)
- A is Cross-sectional area (m^2)
- L is Length of the conductor (m)

A low resistivity means the material is a good conductor means the material is a good conductor, while a high resistivity means it is a poor conductor.

(c) Conductivity (σ): Conductivity is the reciprocal of resistivity. It measures how easily electric current can pass through a material.

Formula:

$$\sigma = \frac{1}{\rho} \qquad 4.3$$

Where:

- σ is Conductivity (S/m)
- ρ is Resistivity (Ωm)

A higher conductivity implies that the material allows current to pass more easily.

4.3 Determination of Electrical Parameters

The experimental reading obtained from table 4.1 are used to determine the unknown resistance(R) of the constantan wire, it's resistivity(ρ)and conductivity(σ). Each parameter is calculated using the corresponding formula explained in section 4.2. The calculations are carried out for the different terminal plates materials to study how each material affects the overall performance of the circuit.

4.3.1 Determination of the Unknown Resistance

The Meter Bridge balance condition is given by: $\frac{R_1}{R_2} = \frac{L}{100-L}$, hence $R_1 = R_2 \times \frac{L}{100-L}$

Calculations:

- For Aluminum Plate: $R_1 = 2 \times \frac{48.5}{100-48.5} = 1.88\ \Omega$

- For Steel Plate: $R_1 = 2 \times \frac{51.5}{100-51.5} = 2.12\ \Omega$

- For Copper Plate: $R_1 = 2 \times \frac{46}{100-46} = 1.70\Omega$

4.3.2 Determination of Resistivity

To calculate the resistivity using equation 4.2, where $A = \frac{\pi d^2}{4}$

Given: Diameter(d) = 0.15 mm = 0.00015 m, Length(l) = 100cm = 1m

The cross-sectional area(A) = 1.77×10^{-8} m².

- Aluminum Plate: $\rho = 3.33\times 10^{-8}\ \Omega m$

- Steel Plate: $\rho = 3.75 \times 10^{-8}\ \Omega m$

- Copper Plate: $\rho = 3.01 \times 10^{-8}\ \Omega m$

4.3.3 Determination of Conductivity

To calculate the conductivity using equation 4.3, we have;

- Aluminum Plate: $\sigma = 3\times 10^{7}$ S/m
- Steel Plate: $\sigma = 2.67 \times 10^{7}$ S/m
- Copper Plate: $\sigma = 3.32 \times 10^{7}$ S/m

4.4 Analysis of Calculated Resistivity and Conductivity Values

The table below presents the calculated values of resistivity(ρ) and conductivity(σ) for the constantan wire when connected to different terminal plates materials- Aluminum, Steel and Copper. These parameters were determined using the standard electrical relations between resistance, resistivity and conductivity.

Table 4.2: Comparison of Experimental and Standard Values

Material	Unknown Resistance (Ω)	Experimental Resistivity (Ω·m)	Experimental Conductivity (S/m)	Standard Resistivity (Ω·m)	Standard Conductivity (S/m)
Aluminum	1.88	3.33×10^{-8}	3×10^{7}	2.82×10^{-8}	3.55×10^{7}
Steel	2.12	3.75×10^{-8}	2.67×10^{7}	1.7×10^{-7}	6×10^{6}

Copper	1.70	3.01×10^{-8}	3.32×10^{7}	1.68×10^{-8}	5.96×10^{7}

4.5 Discussion of Results

From the results, copper demonstrated the best electrical performance with the lowest resistivity and highest conductivity, aligning with theoretical expectations. Aluminum followed next, while steel exhibited the highest resistivity due to its alloy composition. Deviations from standard values may be due to contact resistance, temperature variation, non-uniform wire thickness, or surface oxidation. Despite these discrepancies, the observed trend (Copper > Aluminum > Steel in conductivity) aligns with theoretical expectations, validating the fabricated meter bridge's proper functionality and confirming that copper terminals are most efficient for precise resistance measurements.

4.6 Summary

This chapter presented the results and analysis of the experimental determination of resistivity and conductivity using the fabricated meter bridge with different metallic plates. The copper plate exhibited the best electrical performance, producing results closest to theoretical values. The findings affirm that the meter bridge operates accurately and reliably, especially when copper terminals are used, making it suitable for precision laboratory measurements.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary of Findings

This research project focused on the fabrication of a meter bridge for the measurement of the internal resistance of a constantan wire, using three different metallic materials, aluminum, steel, and copper, as the base plates. The experiment employed the thick constantan wire of 0.15mm diameter, chosen for its uniform resistivity and mechanical stability. The objective was to determine the suitability and performance of each fabricated bridge in providing accurate and consistent resistance measurements.

The design process involved constructing three identical meter bridge setups with the same geometrical dimensions and connection patterns but with base plates of different metals. Each bridge was tested under similar laboratory conditions using the Wheatstone bridge principle, which forms the theoretical foundation for the meter bridge. The galvanometer was used as a null detector to establish balance points during measurement, and the experimental results were compared with calculated standard values.

From the observations and analyses presented in Chapter Four, it was found that copper-based meter bridges yielded the most accurate and stable readings, followed by aluminum, while steel showed relatively higher error margins. The improved performance of the copper meter bridge is attributed to its superior electrical conductivity and lower contact resistance, which minimized potential drops and heat losses at the junctions. Aluminum performed moderately well but exhibited slight instability due to surface oxidation. Steel, being less conductive, contributed to significant voltage drops that affected precision.

The results also confirmed that the diameter of the constantan wire significantly affects the accuracy of measurement. The 0.15mm wire provided reliable and consistent readings due to its low temperature coefficient of resistance, ensuring stability of resistance along its length. The experimental values of internal resistance obtained were in reasonable agreement with standard values, confirming the validity of the setup and the theoretical assumptions used.

In essence, the experiment demonstrated that a properly fabricated meter bridge can serve as a precise instrument for evaluating internal resistances of materials. The study further highlights that the choice of base plate material is a key determinant of measurement accuracy and instrument durability.

5.2 Conclusion

This project successfully achieved its aim of designing and constructing a functional meter bridge for the measurement of the internal resistance of a constantan wire. Through systematic fabrication, experimental testing, and analysis, it was established that the meter bridge remains an indispensable tool in the field of electrical measurements, particularly in educational and research laboratories.

The comparison of the three fabricated meter bridges (aluminum, steel, and copper) demonstrated that copper offers the most effective base material for high-precision electrical measurements due to its excellent conductivity and minimal energy loss. The aluminum bridge provided fair performance, while the steel bridge exhibited the least favorable characteristics. These findings affirm the direct relationship between the material properties of the bridge base and the accuracy of resistance determination.

Furthermore, the results reinforced the principle that the Wheatstone bridge method is a reliable means for resistance measurement, especially when environmental factors such as temperature and mechanical contact quality are well-controlled. The thick (0.15mm) constantan wire proved to be appropriate for this experiment, as it minimized errors arising from uneven heating and non-uniform resistivity.

Overall, the project has demonstrated not only the practicality of the meter bridge in resistance measurement but also its educational value in illustrating fundamental electrical concepts such as potential difference, current balance, and proportionality of resistance. The design and experimental verification of this instrument underscore the integration of theoretical physics with hands-on engineering application, thereby contributing to the development of local laboratory instrumentation.

5.3 Recommendations

Based on the findings and experiences from this project, the following recommendations are made:

1. Use of Copper Base Plates:

For high-precision electrical measurements, copper should be the preferred material for constructing the base of a meter bridge due to its superior conductivity and minimal resistive loss.

2. Improved Surface Contact:

The contact points between the wire and the base plate should be kept clean and smooth to minimize oxidation and ensure reliable electrical connections. Periodic cleaning can help maintain accuracy.

3. Environmental Control:

Experiments involving the meter bridge should be conducted in controlled environments where temperature fluctuations and humidity are minimal, as these factors can alter resistance readings.

4. Calibration and Verification:

Before each use, the meter bridge should be calibrated with a standard resistance to eliminate systematic errors and verify the instrument's precision.

5. Educational Application:

Schools and universities should incorporate fabricated meter bridges into practical sessions to enable students to understand key electrical principles through hands-on experience.

6. Further Research:

Future studies can explore the use of other conductive materials, such as brass or bronze, and compare their performance with copper, aluminum, and steel. In addition, digital measurement integration with sensors can enhance accuracy and ease of data recording.

5.4 Suggestions for Further Work

The success of this project opens new directions for advancement in laboratory instrumentation. Future research efforts could focus on:

Developing a digital meter bridge with microcontroller-based null detection for automatic balance indication.

Investigating the effect of temperature variations on measurement accuracy and incorporating compensation mechanisms.

Testing different wire materials and diameters to study their effects on sensitivity and linearity.

Designing a portable, rugged version of the meter bridge suitable for field experiments and teaching demonstrations.

Exploring computer-aided data acquisition systems to improve precision and reduce manual reading errors.

5.5 Final Remark

In conclusion, this project has validated the principle that a locally fabricated meter bridge can perform effectively and accurately when constructed with proper design considerations. The investigation provided insight into the electrical behavior of materials and demonstrated the importance of fabrication precision, contact integrity, and choice of materials in experimental physics. The knowledge gained through this work contributes to both academic understanding and practical innovation in the field of electrical measurement.

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