BASIC PHYSICS II
EXPERIMENTAL GUIDE

English Version

Basic Electricity,
Magnetism and Optics



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Preface

This practical guide was written as a manual for the Basic Physics 2 practical course in the Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Negeri Surabaya in 2020. This manual covers Electricity, Magnetism, and Optics, divided into two main experiment codes: L for Electricity & Magnetism and O for Optics. Guidelines regarding data analysis, scientific discussions, and plotting experimental graphs are also included.

This Basic Physics 2 manual has been developed using a guided inquiry framework so that students enrolled in the course can actively construct their own knowledge regarding the experiment concepts. Students are provided with the opportunity to design their own experimental procedures to achieve the learning objectives outlined in Section A of each module, and are expected to formulate and test their own hypotheses.

Practical activities in physics education represent a fundamental scientific process. In this guided inquiry guide, physics concepts are studied based on real-world conditions aligned with stated goals. Students are then tasked with designing or refining their problem-solving procedures. The writing team from the Basic Physics Laboratory extends sincere gratitude to all parties who supported the compilation of this guide.

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INTRODUCTION

A. Description of Basic Physics Practicum

At the Faculty of Mathematics and Natural Sciences of Universitas Negeri Surabaya, the Basic Physics course is a common mandatory course that must be taken by students from the Department of Physics in both the Physics Education and Physics Study Programs. The Basic Physics course aims to provide students with an understanding of the foundations of Physics building upon knowledge previously acquired in high school. The topics discussed include Mechanics, Waves and Sound, Thermodynamics, Electricity and Magnetism, Geometric Optics, and the fundamentals of Modern Physics.

In the Basic Physics course, theoretical instruction is complemented by laboratory activities in the Basic Physics laboratory. The scope of the practicum includes introduction to various measuring instruments and training on how to use them, introducing the basics of experimentation and training students to apply them in practical work, as well as developing cognitive strategies that support the understanding of the Basic Physics course.

B. Objectives of Basic Physics Practicum

Basically, Physics laboratory activities can be divided into 3 main areas: (1) conducting measurements of physical quantities, (2) conducting experiments to test the validity of existing theories or laws (practicum), and (3) conducting experiments to discover something new. After completing the Basic Physics Practicum course, students are expected to be able to:

1. Assemble experimental equipment correctly;
2. Use and read measuring instrument scales correctly;
3. Write practicum report abstracts correctly;
4. Write concise theoretical foundations supporting the experiment;
5. Write down experimental procedures;
6. Analyze data along with correct uncertainty/error calculations;
7. Discuss data analysis results;
8. Formulate conclusions; and

In addition, students must be able to collaborate effectively with their group members and conduct practical work in an orderly and disciplined manner.

C. Implementation of Basic Physics Practicum

Technically, the execution of Basic Physics Practicum activities is divided into three stages. The first stage is pre-laboratory activities, the second stage is practicum execution, and the third stage is reporting.

1. Pre-laboratory Stage:

Pre-laboratory activities in the Basic Physics practicum are conducted in groups and serve to equip students so they are prepared to execute a specific practicum topic/title. Basic capabilities required by students prior to conducting the practicum include:

a. Understanding the objectives of the practicum to be performed;
b. Understanding relevant concepts related to the practicum;
c. Being able to identify variables that must be measured and calculated;
d. Understanding specifications and operating procedures of the equipment to be used;

e. Being able to determine required data, methods of data collection, and methods of analysis;
f. Writing Chapter 1 (background, problem statement, and objectives), Chapter 2 (theoretical foundation), and Chapter 3 (equipment and materials, experimental diagrams, variables, and experimental procedures) of the report.

2. Practicum Execution Stage:

During the practicum execution stage, students are trained to act as researchers. Therefore, students are required to be objective, systematic, logical, and thorough. In this stage, student activities involve conducting group practicals according to assigned topics using materials described in this manual. Furthermore, student performance is observed by instructors covering affective (attitudinal) and psychomotor (skill) aspects, which are then scored based on predetermined assessment scales. Aspects evaluated during this execution stage include:

a. Ability to assemble equipment correctly;
b. Ability to use and read measuring instrument scales correctly; and
c. Cooperation among group members.

3. Reporting Stage:

After executing the practicum, students obtain measurement data. These data are processed and analyzed to draft a formal lab report following the standard format attached to this manual. The report will be evaluated by instructors who assign scores according to established guidelines. Report evaluation criteria include:

a. Ability to write an abstract;
b. Ability to write a concise theoretical background supporting the experiment;
c. Ability to formulate experimental procedures;
d. Ability to analyze data along with error propagation calculations and answer questions correctly;
e. Ability to discuss data analysis results; and
f. Ability to formulate conclusions.

D. Assessment of Basic Physics Practicum

Technically, the assessment of the Basic Physics Practicum is conducted at each stage of implementation, namely the pre-laboratory stage, practicum execution stage, and reporting stage.

1. Pre-laboratory Assessment

Pre-laboratory evaluation is conducted on a group basis and serves as the decision criterion for permitting or withholding permission to execute the lab session. Groups that are not yet cleared must repeat the pre-lab activity until deemed eligible. A group is considered eligible when obtaining a minimum score of 60.

No	Item	Interval	Score
1	Understanding lab objectives	1 - 20	
2	Understanding relevant physics concepts	1 - 20	
3	Identifying variables to measure and compute	1 - 20	
4	Understanding tool specifications and operations	1 - 20	
5	Determining data acquisition and analysis methods	1 - 20	
Total			

2. Assessment of experimental work

Experimental work is assessed individually.

No.	Item	Interval	Score
1	Assembling apparatus correctly	1–35	
2	Using measuring instruments and reading their scales correctly	1–35	
3	Cooperating with group members	1–30	
Total			

3. Assessment of reporting

Reports are assessed individually.

No.	Item	Interval	Score
1	Writing an abstract	1–20	
2	Writing a concise theoretical background supporting the experiment	1–20	
3	Formulating the experimental method	1–20	
4	Analyzing data, calculating uncertainties, and answering questions correctly	1–20	
5	Formulating conclusions	1–20	
Total			

4. Final Grade

The final Basic Physics Laboratory grade is determined from the following components

Component	Basis
Participation	Pre-laboratory grade + Experimental-work grade
Assignments	Report grade
Midterm assessment	Seminar grade
Final assessment	Examination grade

$$\text{Final grade} = \frac{(2 \times \text{Participation}) + (3 \times \text{Assignments}) + (2 \times \text{Midterm}) + (3 \times \text{Final})}{10}$$

Grades on the 0–100 scale are converted to the 0–4 scale and letter grades as follows:

Grade Conversion Table

Letter grade	Grade points	Score interval
A	4	85 ≤ score < 100
A−	3.75	80 ≤ score < 85
B+	3.5	75 ≤ score < 80
B	3	70 ≤ score < 75
B−	2.75	65 ≤ score < 70
C+	2.5	60 ≤ score < 65
C	2	55 ≤ score < 60
D	1	40 ≤ score < 55
E	0	0 ≤ score < 40

E. Laboratory Rules

1. Requirements

Students are required to:

a. enter the laboratory at the scheduled time;
b. wear appropriate clothing: shoes, long trousers or a long skirt, and a collared shirt;
c. wear an identification card;
d. submit evidence of permission to conduct the experiment from the laboratory instructor (the pre-laboratory sheet);
e. place all belongings other than the necessary stationery, laboratory manual, and preliminary report sheets in the designated lockers;
f. sign the attendance register;
g. submit the report one week after the experiment;
h. complete the apparatus loan register;
i. work quietly and seriously;
j. return all apparatus clean and neatly arranged;
k. submit the preliminary report to the laboratory assistant or instructor for approval no later than 2 × 24 hours after the start of the laboratory activity;
l. obtain permission from the laboratory assistant or instructor before leaving for any reason;
m. request permission to enter from the laboratory assistant or instructor if arriving late;
n. leave promptly when the laboratory session has ended; and
o. submit the formal laboratory report according to the established schedule

2. Prohibitions

Students must not:

a. violate agreed written or unwritten requirements;
b. eat or drink in the laboratory;
c. use apparatus other than that specified without permission from the laboratory assistant or instructor;
d. move to a laboratory bench other than the one assigned;
e. disturb or interfere with another group's work;
f. alter or replace experimental apparatus without permission from the laboratory assistant or technician;
g. conduct experiments outside scheduled laboratory hours without a laboratory assistant or instructor present;
h. manipulate data so that they no longer reflect the experimental results;
i. damage laboratory equipment, whether intentionally or unintentionally; or
j. miss a scheduled experiment without a valid reason or permission.

3. Penalties

Violations may result in:

a. an immediate verbal warning;
b. being refused entry to, or being removed from, the Basic Physics Laboratory during the session;
c. a reduction in grades; or
d. the group being required to replace the damaged equipment with an equivalent item or have it repaired.

F. Laboratory Reports

The formal Basic Physics laboratory report is prepared after the preliminary report has been approved by the laboratory assistant or instructor. The following requirements apply:

1. Write in black ink.
2. Use the abstract and preliminary-report sheets specified by the laboratory.
3. Use plain, unruled F4 paper.
4. Use margins of 3 cm on the left and 2 cm at the top, right, and bottom.
5. Figures and graphs may be printed and pasted into the report.
6. Bind the report neatly

The structure of the formal report and an explanation of each part are given below.

ABSTRACT

A single paragraph of approximately 120 words briefly describing the laboratory activity. Include the title, objectives, main activities, experimental variables, numerical final results, and conclusions. Place keywords below the abstract.

CHAPTER I INTRODUCTION

A. Background: Explain the reasons for conducting the experiment.

B. Research questions: State concise questions that the experiment is intended to answer.

C. Objectives: Describe what is to be achieved by conducting the experiment.

CHAPTER II THEORETICAL BACKGROUND

Present the material needed to support the experiment and provide the basis for analyzing the data. Include relevant concepts, equations, and figures, with a minimum length of two pages.

CHAPTER III EXPERIMENTAL METHODOLOGY

A. Apparatus and materials:

List the apparatus and materials required for the experiment.

B. Experimental diagram:

Provide a drawing of the experimental arrangement.

C. Experimental variables:

(1) Controlled variables are deliberately kept unchanged.

(2) Independent or manipulated variables are deliberately varied.

(3) Dependent or response variables change in response to changes in the manipulated variables.

D. Experimental procedure:

Describe the steps carried out in the experiment as a numbered or bulleted sequence.

CHAPTER IV DATA AND ANALYSIS

A. Data: Present the processed experimental data as tables, graphs, figures, or descriptions.

B. Analysis: Explain how the data are analyzed to obtain the final results.

C. Answers to questions: Answer the questions provided for the experiment.

CHAPTER V CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions: Explain the final experimental results in relation to the objectives and research questions.

B. Recommendations: Provide suggestions concerning the conduct of the experiment.

REFERENCES

List the sources used to prepare the formal report. Sources may include books and reliable internet materials.

PRELIMINARY REPORT

Present the data recorded during the laboratory activity, endorsed by the laboratory assistant or instructor.

APPENDICES

Include material not presented in the main report, such as calculations used to obtain the results and the stated level of precision, as well as supporting figures.

MEASUREMENT UNCERTAINTY AND SIGNIFICANT FIGURES

A. Measurement Uncertainty and Error

Every measurement of a physical quantity inevitably involves uncertainty. The precision, accuracy, and reliability of an experimental measurement depend strongly on how accurately its uncertainty can be estimated. For example, a resistance measured using an accurate digital multimeter may be reported as 20.03 ± 0.01 Ω. This means that the true resistance is expected to lie between 20.02 Ω and 20.04 Ω. The interval in which the expected value lies represents the measurement uncertainty. It also expresses the accuracy or precision of the measured data: a narrower interval indicates greater precision and accuracy, and vice versa.

The difference between the true value of a quantity and its measured value is often called the measurement "error." The source suggests that this difference is more appropriately described as a "deviation," while reserving "error" for a mistake in the general sense.

In many measurements, the true value of a quantity is unknown and may even be unknowable. For example, two groups of students may measure the same physical quantity using the same apparatus and experimental method, with comparable care, yet obtain slightly different results: (5.00 ± 0.02) and (5.02 ± 0.02). Each group may claim that its error is smaller than the other's. In this situation, however, both groups may have worked correctly: they followed the appropriate procedure and used appropriate measurement precision. Their slightly different results do not necessarily indicate that either group made a mistake.

B. Why Measurement Uncertainty Matters

Consider the resistance measurement above. When the resistor is heated to 100 °C, its measured resistance becomes 20.04 Ω. What does this imply? If the values before and after heating, 20.03 Ω and 20.04 Ω, are used without considering uncertainty, we would conclude that the resistance increased by 20.04 − 20.03 = 0.01 Ω. However, if the uncertainty at 100 °C is also ±0.01 Ω, the true resistance may have remained unchanged or even decreased. The change in resistance could therefore lie between −0.01 Ω and +0.03 Ω. This example, like many others, shows why measurement uncertainty must be considered in experimental work: it indicates how accurately and precisely the measured data represent the true value. More generally, there are three principal reasons for considering uncertainty and measurement precision whenever experimental data are collected:

1. Other users of the data need to know their accuracy and precision for their own purposes.
2. Hypotheses based on the data must be formulated and tested appropriately.
3. The history of the natural sciences shows that theoretical and measured values of physical quantities differ, however slightly, even as experimental apparatus, methods, and procedures become more advanced.

C. Sources of Uncertainty

1. Systematic uncertainty

Systematic uncertainty arises from faults in the use of an instrument or faults already present in the instrument itself. If the cause lies in the instrument, the same uncertainty will recur whenever it is used. Examples include the following.

a. Instrument errors.

An incorrectly calibrated scale produces readings that differ from the correct value. For example, a current that should be 2 A may consistently be measured as 2.3 A by an ammeter. This can be addressed by
(1) calibrating the instrument so that it reads correctly or
(2) replacing it with a more precise instrument.

b. Zero errors.

These occur when the instrument does not indicate zero when it should, or has a nonzero reading before use. Ensure that the instrument reads zero before taking measurements.

c. Inappropriate response timing.

Uncertainty arises when a reading is taken at a different time from the event that should have been measured. A common laboratory problem is taking a reading after the desired condition has passed. For example, when intending to record the temperature of heated water at 70 °C, the reading may instead be taken at a higher temperature.

d. Improper conditions.

The instrument may not be suitable for the measurement conditions. For example, a metal ruler is unsuitable for measuring the length of an object at a high temperature because the ruler itself expands.

2. Random uncertainty

Random uncertainty commonly appears in repeated measurements, causing results to vary around their mean. Results may differ because:
(a) each measurement is made at a different moment;
(b) the measuring instrument introduces uncertainty; or
(c) other sources of uncertainty are associated with taking the measurements.

3. Human errors

Insufficient skill in operating or reading a measuring instrument can introduce errors, such as parallax errors or calculation mistakes.

D. Determining Measurement Uncertainty

The following basic methods are suitable for laboratory work in the common first-year program.

1. Uncertainty in a single measurement

A direct, single measurement of x is reported as $\mathbf{x \pm \Delta x}$, where **x** is the instrument reading and Δx is the absolute uncertainty. The absolute uncertainty is taken as half the smallest scale division readable on the instrument.

$$\textbf{Percentage uncertainty} = \frac{\mathbf{\Delta x}}{\boldsymbol{x}} \times \mathbf{100\%}$$

$$\text{Precision level} = 100\% - \text{Percentage uncertainty}$$

Example:

A ruler gives a distance of 10 cm. Its smallest scale division is 1 mm, or 0.1 cm. Then:

$$s = 10 \text{ cm}$$

$$\Delta s = 0.1 \times 0.5 = 0.05 \text{ cm}$$

The result is written as:

$$(10.00 \pm 0.05) \text{ cm}$$

$$\text{Percentage uncertainty} == \frac{\mathbf{0{,}05}}{\mathbf{10}} \times 100\% = 0.50\%$$

$$\text{Precision level} = 100\% - 0.50\% = 99.50\%$$

2. Uncertainty in repeated measurements

For n repeated measurements of x, the final result is written as $\bar{x} \pm \Delta x$, where $\bar{x}$ is the mean and Δx is the absolute uncertainty.

$$\textbf{Percentage uncertainty} = \frac{\mathbf{\Delta x}}{\boldsymbol{x}} \times \mathbf{100\%}$$

$$\textbf{Precision level} = \mathbf{100\% - \text{Percentage uncertainty}}$$

Example:

No.	(s ± Δs) cm	δ	δ²
1	10	0.0	0.00
2	10.2	0.2	0.04
3	10.1	0.1	0.01
4	10	0.0	0.00
5	10	0.0	0.00
6	9.9	-0.1	0.01
7	10.1	0.1	0.01
8	9.8	-0.2	0.04
9	9.9	-0.1	0.01
10	10	0.0	0.00
n = 10	Σs = 100	Σδ = 0	Σδ² = 0.12

Several methods can be used to determine the final result.

a. Method 1

$$\bar{s} = \frac{(s_{max} + s_{min})}{2} = \frac{(10{,}2 + 9{,}8)}{2} = 10 \text{ cm}$$

$$\Delta s = \frac{(s_{max} - s_{min})}{2} = \frac{(10{,}2 - 9{,}8)}{2} = 0.2 \text{ cm}$$

Result : (10.00 ± 0.2) cm

Percentage uncertainty : $\frac{0{,}2}{10} \times 100\% = 2.0\%$

Precision level : 100% − 2% = 98.0%

b. Method 2

$$\bar{s} = \frac{\Sigma s}{n} = \frac{100}{10} = 10 \text{ cm}$$

$$\Delta s = \delta_{max} = 0.2 \text{ cm}$$

Result : (10.00 ± 0.2) cm

Percentage uncertainty : $\frac{0{,}2}{10} \times 100\% = 2.0\%$

Precision level :100% − 2% = 98.0%

c. Method 3

$$\bar{s} = \frac{\Sigma s}{n} = \frac{100}{10} = 10 \text{ cm}$$

$$\Delta s = \sqrt{\frac{\Sigma \delta^2}{n}} = \sqrt{\frac{0{,}12}{10}} = \sqrt{0{,}012} = 0.11 \text{ cm}$$

Result : (10.00 ± 0.11) cm

Percentage uncertainty : $\frac{0{,}11}{10} \times 100\% = 1.10\%$

Precision level : 100% − 1.1% = 98.90%

d. Method 4

$$\bar{s} = \frac{\Sigma s}{n} = \frac{100}{10} = 10 \text{ cm}$$

$$\Delta s = \sqrt{\frac{\Sigma \delta^2}{(n-1)}} = \sqrt{\frac{0{,}12}{10}} = \sqrt{0{,}01} = 0.1 \text{ cm}$$

Result : (10.00 ± 0.1) cm

Percentage uncertainty : $\frac{0{,}1}{10} \times 100\% = 1.0\%$

Precision level : 100% − 1.1% = 98.90%

e. Method 5

$$\bar{s} = \frac{\Sigma s}{n} = \frac{100}{10} = 10 \text{ cm}$$

$$\Delta s = \sqrt{\frac{\Sigma \delta^2}{n(n-1)}} = \sqrt{\frac{0{,}12}{90}} = \sqrt{0{,}0013} = 0.04 \text{ cm}$$

Result : (10.00 ± 0.04) cm

Percentage uncertainty : $\frac{0{,}04}{10} \times 100\% = 0{,}40\%$

Precision level : 100% − 0.40% = 96.60%

f. Method 6

$$\bar{s} = \frac{\Sigma s}{n} = \frac{100}{10} = 10 \text{ cm}$$

$$\Delta s = \frac{1}{n}\sqrt{\frac{n\Sigma\delta^2 - (\Sigma\delta)^2}{n(n-1)}} = \frac{1}{10}\sqrt{\frac{10(0{,}12) - 0}{9}} = 0{,}036 \text{ cm}$$

Result : (10.00 ± 0.036) cm

Percentage uncertainty : $\frac{0{,}036}{10{,}000} \times 100\% = 0{,}36\%$

Precision level : 100% − 0,36% = 99.6%

E. Calculations with Uncertain Quantities

1. Addition and subtraction

If X = (x ± Δx) and Y = (y ± Δy), and R = X ± Y, then R = r ± Δr, where:

$$\mathbf{r = x \pm y \quad and \quad \Delta r = \Delta x + \Delta y}$$

Example:

If A = B + C and D = B – C

with B = (10.0 ± 0.2) m and C = (5.0 ± 0.1) m,

then A = (15.0 ± 0.3) m and D = (5.0 ± 0.3) m.

2. Multiplication and division

If X = (x ± Δx) is a derived quantity and a, b, c, … are its constituent quantities, with uncertainties Δa, Δb, Δc, … respectively, Δx is obtained using the differential rule:

$$\Delta x = \left|\frac{\partial x}{\partial a}\right|\Delta a + \left|\frac{\partial x}{\partial b}\right|\Delta b + \left|\frac{\partial x}{\partial c}\right|\Delta c + \cdots$$

Example 1

The measured length, width, and thickness of a rectangular block are (20 ± 0.05) cm, (10 ± 0.05) cm, and (5 ± 0.05) cm, respectively. What are its volume and uncertainty?

Solution: The volume of the block is:

$$V = l \times w \times t$$

$$V = 20 \times 10 \times 5 = 1000 \text{ cm}^3$$

Its volume uncertainty is:

$$\Delta V = \left|\frac{\partial V}{\partial p}\right|\Delta l + \left|\frac{\partial V}{\partial l}\right|\Delta w + \left|\frac{\partial V}{\partial t}\right|\Delta t$$

$$\Delta V = (wt\Delta l) + (lt\Delta w) + (lw\Delta t)$$

$$\Delta V = (10 \times 5 \times 0.5) + (20 \times 5 \times 0.5) + (20 \times 10 \times 0.5)$$

$$\Delta V = 25 + 50 + 100 = 175 \text{ cm}^3$$

The result is written as:

$$(1000 \pm 175) \text{ cm}^3$$

$$\text{Percentage uncertainty} = (175 / 10) \times 100\% = 17.50\%$$

$$\text{Precision level} = 100\% - 17.5\% = 82.50\%$$

Example 2

The measured mass and volume of a liquid are (1000 ± 0.05) g and (1000 ± 175) cm³, respectively. What are its density and uncertainty?

Solution:

The density of the liquid is:

$$\rho = \frac{m}{v} = \frac{1000}{1000} = 1 \text{ g/cm}^3$$

The uncertainty calculation is presented in the source as:

$$\Delta\rho = \left|\frac{\partial \rho}{\partial m}\right|\Delta m + \left|\frac{\partial \rho}{\partial V}\right|\Delta V$$

$$\Delta V = \left(\left|\frac{1}{V}\right| \Delta m\right) + \left(\left|\frac{m}{V^2}\right| \Delta V\right)$$

$$\Delta V = \left(\left|\frac{1}{1000}\right| 0{,}05\right) + \left(\left|\frac{1000}{1000^2}\right| 175\right)$$

$$\Delta V = 0.00005 + 0.175 = 0.17505 \text{ g/cm}^3$$

The result is written in the source as:

$$1 \pm 0.17505 \text{ cm}^3$$

$$\text{Percentage uncertainty} = \frac{0.17505}{1} \times 100\% = 17.505\%$$

$$\text{Precision level} = 100\% - 17.505\% = 82.495\%$$

F. Graphs

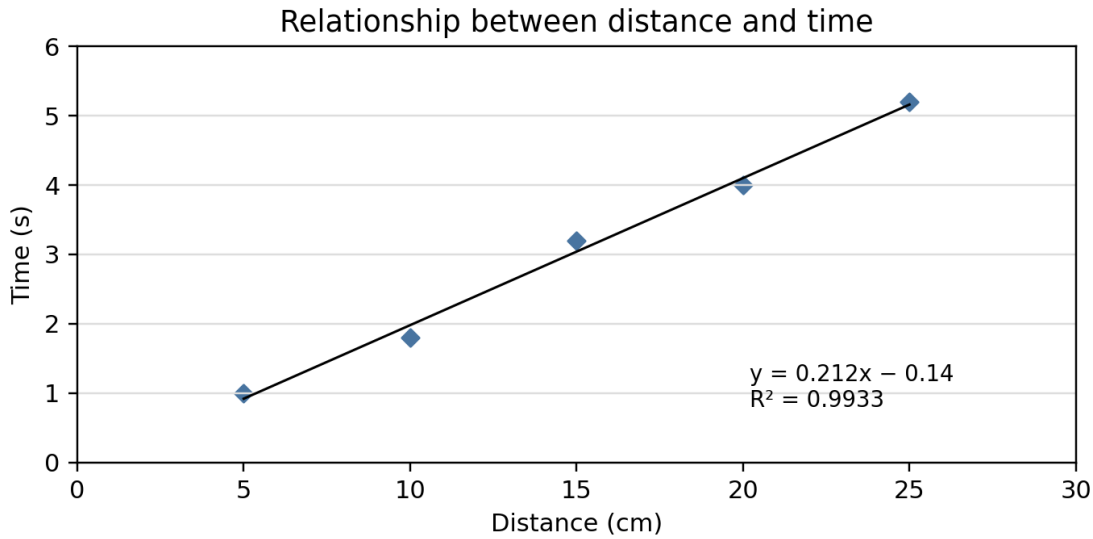
A graph can show the relationship between two variables. A linear graph follows y = mx + c, where c is the y-intercept and m is the gradient or slope. To determine a quantity experimentally using a graph, place the dependent-variable term on the y-axis and the independent-variable term on the x-axis so that m contains the quantity being sought. The source expresses the graph's precision level as $R^2 \times 100\%$.

Example 1: For t = s/v, plot t on the y-axis and s on the x-axis. Then m = 1/v, so v = 1/m.

Example 2: For $t^2 = 2s/a$, plot t^2 on the y-axis and s on the x-axis. Then m = 2/a, so a = 2/m.

Note: Choose the variables plotted to match the research objective. The gradient should allow the required quantity to be determined while still showing the effect of the manipulated variable on the response variable.

Example:



The graph places time t on the y-axis and distance s on the x-axis. From t = s/v, the slope m is 1/v, so v = 1/m. The graph gives m = 0.212, hence v = 1/0.212 = 4.717 cm/s. The stated precision level is 0.9933 × 100% = 99.33%.

G. Significant Figures

When reporting laboratory measurements, the rules for significant figures must be observed. The number of significant figures reported reflects the precision of a measurement. Significant figures are the digits in a numerical result obtained from experimental measurements. Their number indicates the accuracy and precision with which a particular quantity has been measured.

1. Rules for significant figures

a. If a decimal point is present, the rightmost digit, whether zero or nonzero, is the rightmost significant figure.
b. If there is no decimal point, the rightmost nonzero digit is the rightmost significant figure.
c. Whether or not there is a decimal point, the leftmost nonzero digit is the leftmost significant figure.
d. All digits between the leftmost and rightmost significant figures are significant.

2. Significant figures in measurement results

Significant figures in a measurement consist of certain digits and an estimated digit. The estimated digit is also called the uncertain digit. The more precise the measurement, the more significant figures are reported. For example, a ruler with a smallest division of 0.1 cm gives a length

X = 12.5 cm and has an uncertainty of ±0.05 cm.

The result is written as:

X = (12.50 ± 0.05) cm

3. Rounding significant figures

To reduce the number of significant figures, some digits must be discarded. If the first discarded digit is:

a. less than five, do not round up;

b. greater than five, round up;

c. equal to five, round up if the preceding retained digit is odd.

4. Calculations with significant figures

a. Addition and subtraction.

Carry out the calculation to the first decimal position containing an estimated digit. In the source, underlining indicates estimated digits. Example:

$$1482.372 + 13.8 + 1.49 = 1497.5$$

b. Multiplication and division.

According to the source, the result of multiplying or dividing two or more numbers should contain one more significant figure than the smallest number of significant figures in the input values. Example:

$$1.55 \times 72.431 \times 125.025 = 14036.31295$$

The value 1.55 has the fewest significant figures, namely 3. The result is therefore reported with 3 + 1 = 4 significant figures. Rounding 14036.31295 to four significant figures gives 14040, or 1.404×10^4.

H. Operational Definitions of Variables

An operational definition describes what a variable means in the context of an experiment. It is necessary to ensure that measurements or data collection are consistent across data sources. In addition to defining a variable operationally, specify the measurement method, the measurement result or category, and the measurement scale used. The source introduces an example involving a viscosity experiment with mass as the independent variable.

The mass of each sphere is first measured using a digital balance. Two mass settings are used: $0.0057 \pm (5 \times 10^{-4})$ kg and $0.001 \pm (5 \times 10^{-4})$ kg.

L0 ELECTRIC MEASURING INSTRUMENTS

A. EXPERIMENTAL OBJECTIVES

Experiment 1 (Multimeters):

2. Use analog and digital multimeters correctly as ammeters and read their indications accurately.
3. Use analog and digital multimeters correctly as voltmeters and read their indications accurately.
4. Use analog and digital multimeters correctly as ohmmeters and read their indications accurately.
5. Compare resistance values determined from resistor color bands with direct measurements using analog and digital multimeters.

Experiment 2 (Galvanometer):

6. Determine the direction of current in a closed circuit using a galvanometer.

Experiment 3 (Slide-wire rheostat):

7. Measure the resistance of a slide-wire rheostat.

B. THEORETICAL BACKGROUND

1. Multimeters



Analog and digital multimeters

A multimeter, or multitester, is an electrical measuring instrument often called a VOM (volt-ohm meter). It can measure voltage (as a voltmeter), resistance (as an ohmmeter), and current (as an ammeter). There are two categories: digital multimeters (DMMs), which are the newer type and generally provide more accurate readings, and analog multimeters. Both categories can measure AC and DC electrical quantities. A multimeter may be a handheld device used for troubleshooting and fieldwork, or an instrument capable of measurements with very high precision.

2. Galvanometers



Galvanometer

A galvanometer is an electrical instrument used to measure relatively small currents and potential differences. Its internal components do not permit direct measurement of large currents or potential differences. Its range can be extended using an external resistor: a series multiplier resistor for a voltmeter, or a shunt resistor for an ammeter.

3. Slide wire rheostats



Slide-wire rheostat

A sliding contact is used to increase or decrease resistance. A trimmer is a variable resistor commonly fitted to a printed circuit board (PCB). A widely used type is the three-terminal trimmer potentiometer, or trimpot, which can be connected as a rheostat.

C. EXPERIMENTAL METHOD

1. Apparatus and materials

Experiment 1

No.	Apparatus or material	Quantity
1	Wire board	1
2	Analog multimeter	1
3	Digital multimeter	1
4	Resistors of various values (color-banded and white-bodied resistors)	6
5	DC voltage source	As required
6	Connecting leads	As required

Experiment 2

No.	Apparatus or material	Quantity
1	Galvanometer	1
2	Battery holder kit	As required
3	Battery (1.5 V)	1

Experiment 3

No.	Apparatus or material	Quantity
1	Slide-wire rheostat	1
2	Multimeter	1

2. Experimental procedure

Translator's note: The source provides this heading but no experimental steps. The space below is retained for the procedure.

L1 WIRE RESISTIVITY

A. EXPERIMENTAL OBJECTIVES

1. Determine the electrical resistivity of a wire.
2. Analyze the effect of wire cross-sectional area on its electrical resistance.

B. THEORETICAL BACKGROUND

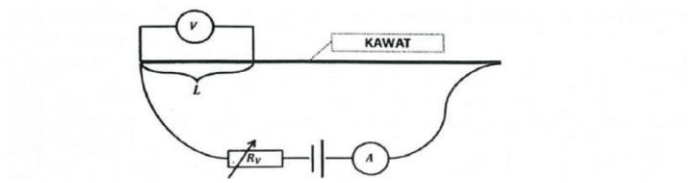


Figure 1. Circuit for determining the resistivity of a wire

$$R = \rho L / A \quad (1)$$

R = resistance (Ω);
ρ = electrical resistivity (Ω·m);
L = wire length (m);
A = wire cross-sectional area (m^2).

C. EXPERIMENTAL METHOD

A. Apparatus and Materials

No.	Apparatus or material	Quantity
1	Wire board	1
2	Thick copper wire	1 roll
3	Thin copper wire	1 roll
4	Thick nichrome wire	1 roll
5	Thin nichrome wire	1 roll
6	Batteries	3
7	Battery holders	3
8	Slide-wire rheostat	1
9	Micrometer screw gauge	1
10	Analog multimeter	1
11	Digital multimeter	1
12	Scissors	1
13	Connecting leads	8
14	Ruler	1
15	Sandpaper	As required

B. Experimental procedure

1. Measure the wire diameter d using a micrometer screw gauge.
2. Assemble the circuit as shown in Figure 1.
3. Adjust the rheostat to keep the current I from becoming too large.
4. Determine the length L of wire to be used.
5. Use a multimeter to measure the potential difference V across length L and the current through the wire.
6. Repeat the experiment for at least five different wire lengths.
7. Repeat the experiment for at least two different wire diameters.
8. Repeat the experiment for at least two different wire materials.

C. Data table

Wire resistivity measurements

Wire type	Trial	d ± Δd	L ± ΔL	V ± ΔV	I ± ΔI
	1				
	2				
	3				
	4				
	5				

L2 OHM'S LAW

A. EXPERIMENTAL OBJECTIVES

A. Verify Ohm's law for the experimental circuit.
B. Compare the resistance obtained experimentally with the value determined from resistor color bands and by direct measurement.
C. Analyze current and potential difference in simple, series, and parallel circuits.

B. THEORETICAL BACKGROUND

Ohm's law states that, for a metallic conductor at constant temperature, the ratio of the potential difference ΔV between two points to the current I through the conductor is constant (Alonso, 1994, p. 77). Equivalently, the current through a wire is directly proportional to the applied voltage (Tipler, 2001, p. 142).

$$V = I.R \quad \text{(Tipler, 2001)}$$

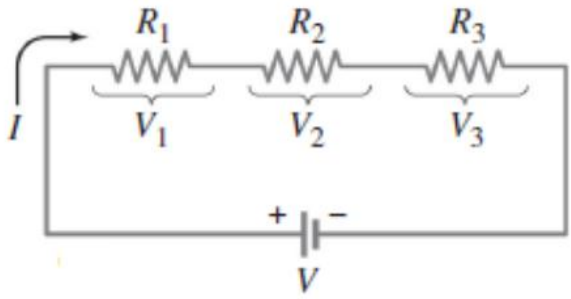
V = potential difference (V);
I = electric current (A);
R = circuit resistance (Ω).

❖ Series circuits

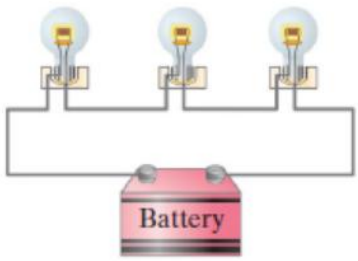
When several resistors are connected in series, their total resistance is:

$$R_x = R_1 + R_2 + R_3 \quad \text{(Tipler, 2001)}$$

A series circuit has only one path for current. The current I is therefore the same throughout the circuit. Ohm's law can be applied either to the complete circuit or to each section individually.



Series resistor circuit (Giancoli, 2014)

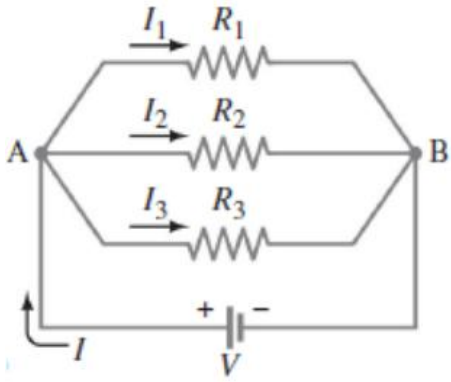


Physical arrangement of resistors in series (Giancoli, 2014)

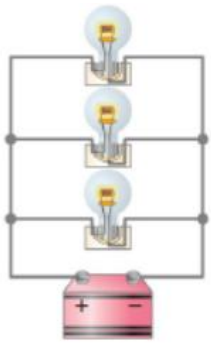
❖ **Parallel circuits**

A parallel circuit consists of two or more resistors connected in parallel branches. Like a series circuit, it can be represented by an equivalent resistance.

$$1/R_{total} = 1/R_1 + 1/R_2 + 1/R_3 + \cdots + 1/R_n \quad \text{(Tipler, 2001)}$$

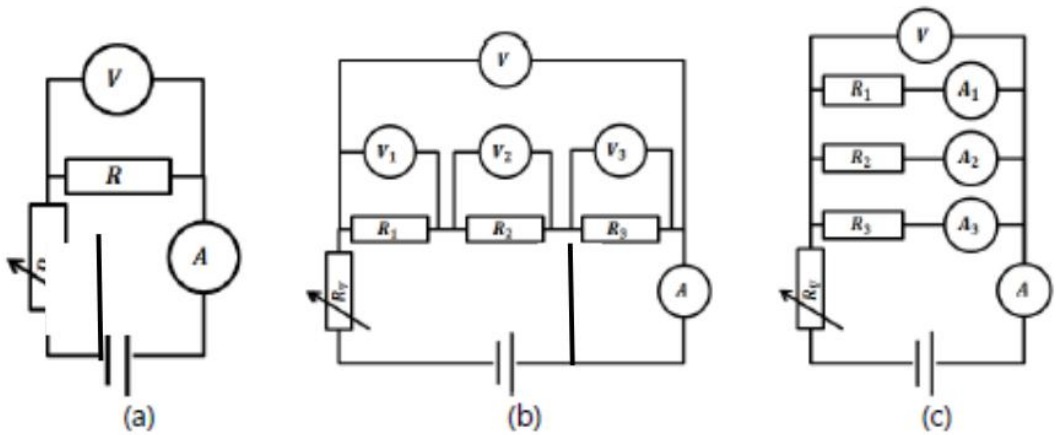


Parallel resistor circuit (Giancoli, 2014)



Physical arrangement of resistors in parallel (Giancoli, 2014)

Experimental circuits



Experimental circuits: (a) simple circuit; (b) series circuit; (c) parallel circuit

C. EXPERIMENTAL METHOD

A. Apparatus and materials

No.	Apparatus or material	Quantity
1	Batteries	3
2	Analog multimeters	2
3	Resistors	8
4	Battery holder kit	1
5	Circuit board kit	1
6	Connectors	4
7	Connecting leads	4

B. Experimental Procedure

❖ **Resistor Values**

Reading resistor color bands:

1. Observe the colors of the bands on each resistor.
2. Determine the resistance by comparing the bands with the resistor color-code table.

Measuring resistance with a multimeter:

1. Connect the resistor to the multimeter.
2. Read the resistance indicated by the multimeter.

❖ **Simple circuit**

1. Assemble the components on the circuit board as shown in circuit (a), using a resistor whose resistance has been measured.
2. Measure the voltage V across the resistor using a multimeter.
3. Measure the circuit current I using a multimeter.
4. Repeat the experiment using at least three different resistor values.

❖ **Series circuit**

1. Assemble the components on the circuit board as shown in circuit (b), using resistors whose resistances have been measured.
2. Measure the voltage across each resistor (V_1, V_2, and V_3) using a multimeter.
3. Measure the total voltage V_t across the resistors using a multimeter.
4. Measure the circuit current I using a multimeter.
5. Repeat steps 1–4 using at least three different supply voltages.

❖ **Parallel circuit**

1. Assemble the components on the circuit board as shown in circuit (c), using resistors whose resistances have been measured.
2. Measure the voltage V across each resistor using a multimeter.
3. Measure the branch currents I_1, I_2, and I_3 using a multimeter.
4. Measure the total circuit current I_t using a multimeter.
5. Repeat steps 1–4 using at least three different supply voltages.

D. Data Tables

❖ Resistor values

No.	Band colors	Color-code value (Ω)	Multimeter value (Ω ± ΔΩ)
1			
2			
3			

❖ Simple circuit

No.	R (Ω)	(V ± ΔV) V	(I ± ΔI) A
1			
2			
3			

❖ Series circuit

No	(V ± ΔV) V	(V_1 ± ΔV) V	(V_2 ± ΔV) V	(V_3 ± ΔV) V	(I ± ΔI) A
1					
2					
3					

❖ Parallel circuit

No.	(V ± ΔV) V	(I_1 ± ΔI) A	(I_2 ± ΔI) A	(I_3 ± ΔI) A	(I ± ΔI) A
1					
2					
3					

L3 KIRCHHOFF'S LAW

A. EXPERIMENTAL OBJECTIVES

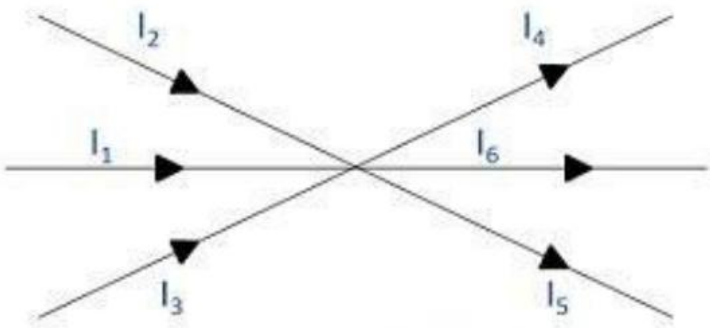
1. Verify Kirchhoff's first and second laws in closed electrical circuits.
2. Describe the characteristics of series and parallel circuits.
3. Compare currents in different closed-circuit arrangements.

B. THEORETICAL BACKGROUND

The voltages across circuit elements and the currents through them are governed by Kirchhoff's two laws. Historically, Gustav Robert Kirchhoff (1824–1887) developed his analysis by drawing on Faraday's treatment of electrical induction, Oersted's connection between force and electric current, and Ohm's relationship between voltage and current.

a. Kirchhoff's first law

Kirchhoff's current law states that the sum of currents entering a junction equals the sum of currents leaving it. Equivalently, the algebraic sum of currents at a junction is zero.



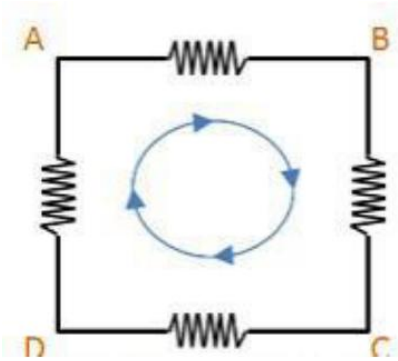
Currents entering and leaving a junction

$$I_1 + I_2 + I_3 = I_4 + I_5 + I_6$$

This law follows from conservation of charge: charge entering a junction must leave it, because charge does not accumulate at the junction.

b. Kirchhoff's second law

Kirchhoff's voltage law states that the algebraic sum of voltages around a closed loop is zero. It follows from conservation of energy and the conservative character assumed for the circuit. One method that reduces sign errors is to traverse the loop clockwise, writing a positive term for an element when its positive terminal is encountered first and a negative term when its negative terminal is encountered first.



Voltages around a closed loop

$$V_{a\beta} + V_{\beta}c + Vcd + Vd_{a} = 0$$

Kirchhoff's laws are commonly used to analyze branched circuits. The source then states that Kirchhoff's law is difficult to apply to these circuits. In an unbranched circuit, the current is the same at every point; in a branched circuit, the total current entering a junction equals the total current leaving it, as stated by the first law. Complex networks can be analyzed using Kirchhoff's laws. A junction is a point where several conductors meet. A loop is a closed conducting path.

C. EXPERIMENTAL METHOD

A. Apparatus and materials

No.	Apparatus or material	Quantity
1	Multimeters	2
2	DC voltage sources	As required
3	Resistors	As required
4	Slide-wire rheostat	1
5	Connecting leads	As required
6	Circuit board	1
7	Ohmmeters	2

B. Experimental procedure

❖ **Kirchhoff's first law**

1. Assemble the experimental circuit as illustrated.
2. Measure the total current and the current through each resistor.
3. Measure the total circuit voltage and the voltage across each resistor.
4. Repeat steps 1–3 with a different supply voltage.
5. Calculate the resistance of each resistor from its measured voltage and current.
6. Compare each calculated resistance with the value measured directly using a multimeter.

❖ **Kirchhoff's second law**

1. Assemble the experimental circuit.
2. Measure the voltage of each source.
3. Measure the current through resistor 1 (I_1), through resistor 2 (I_2), and through the branch shared by the two loops (I_3).
4. Measure the resistances using a multimeter.
5. Calculate the shared-branch current I_3 using Kirchhoff's second law.
6. Compare the calculated and measured values of I_3.
7. Repeat steps 1–6 after reversing the polarity of the voltage source.

C. Data Tables

❖ **Kirchhoff's first law**

No.	V total	V_1	V_2	V_3	I total	I_1	I_2	I_3	R calculated	R measured
1										
2										
3										
4										
5										
6										

❖ **Kirchhoff's second law**

No.	V_1	V_2	R_1	R_2	I_1	I_2	I_3	I_3 calculated
1								
2								
3								
4								
5								
6								

L4 WHEATSTONE BRIDGE

A. EXPERIMENTAL OBJECTIVES

1. Determine the resistance of a resistor using the Wheatstone-bridge principle and compare the result with a direct multimeter measurement.

B. THEORETICAL BACKGROUND

Wheatstone bridge

A circuit containing four resistances, with a voltage source connected across one pair of opposite vertices and a galvanometer connected across the other pair, is called a Wheatstone bridge (Figure 1).

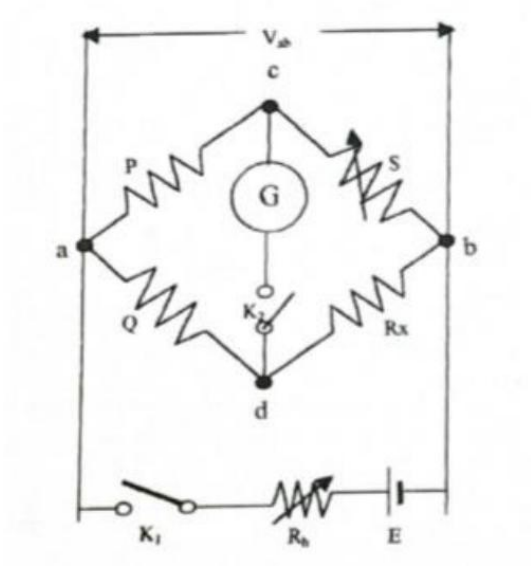


Figure 1. Wheatstone bridge

Suppose that K_1 remains closed and K_2 is open. If the voltage across terminals a–b is $V_{a\beta}$, the voltages across c–b and d–b are:

$$V_{c\beta} = [S / (P + S)]\ V_{a\beta} \qquad (1)$$

$$V_{d\beta} = [R_x / (Q + R_x)]\ V_{a\beta} \qquad (2)$$

By adjusting S, it is possible to make $V_{c\beta} = V_{d\beta}$. When this condition is met, no current flows through the galvanometer even if K_2 is closed. If G shows no deflection, the bridge is balanced and:

$$(P + S) / S = (Q + R_x) / R_x \qquad (3)$$

$$P / S = Q / R_x \qquad (4)$$

C. EXPERIMENTAL METHOD

A. Experimental arrangement

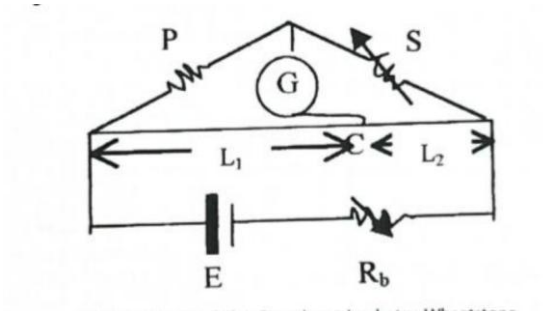


Figure 2. Slide-wire Wheatstone-bridge arrangement

B. Apparatus and materials

No.	Apparatus or material	Quantity
1	Multimeter	1
2	Galvanometer	1
3	Resistors	As required
4	Slide-wire rheostat	1
5	Connecting leads	As required
6	Circuit board	1
7	Wire	As required

C. Experimental procedure

❖ **Resistor values**

Reading resistor color bands:

1. Observe the colors of the bands on each resistor.
2. Determine the resistance using the color-code table.

Measuring resistance with a multimeter:

1. Connect the resistor to the multimeter.
2. Read the resistance indicated by the multimeter.

❖ **Wheatstone bridge**

1. Assemble the apparatus as shown in Figure 2.
2. Select the resistor whose resistance is to be measured.
3. Set the rheostat close to its maximum resistance to limit the current and prevent the wire from heating.
4. Close the switch, then move the sliding contact slowly until the galvanometer reads zero. Choose a suitable resistance-box setting so that the balance point is not too close to either end of the wire.
5. Measure L_1 and L_2 and enter the experimental data in the table.
6. Repeat steps 1–5 using different resistance-box settings for the same type of lamp.

D. Data tables

❖ Resistor values

No.	Band colors	Color-code value	Multimeter resistance
1			
2			
3			
4			
5			

❖ Wheatstone bridge

Trial	R	L_1	L_2
1			
2			
3			
4			
5			

L5 RL AND RC CIRCUITS

A. EXPERIMENTAL OBJECTIVES

1. Determine inductive and capacitive reactance.
2. Determine the inductance L of an inductor and the capacitance C of a capacitor.
3. Describe the behavior of inductors and capacitors connected to AC and DC voltage sources.

B. THEORETICAL BACKGROUND

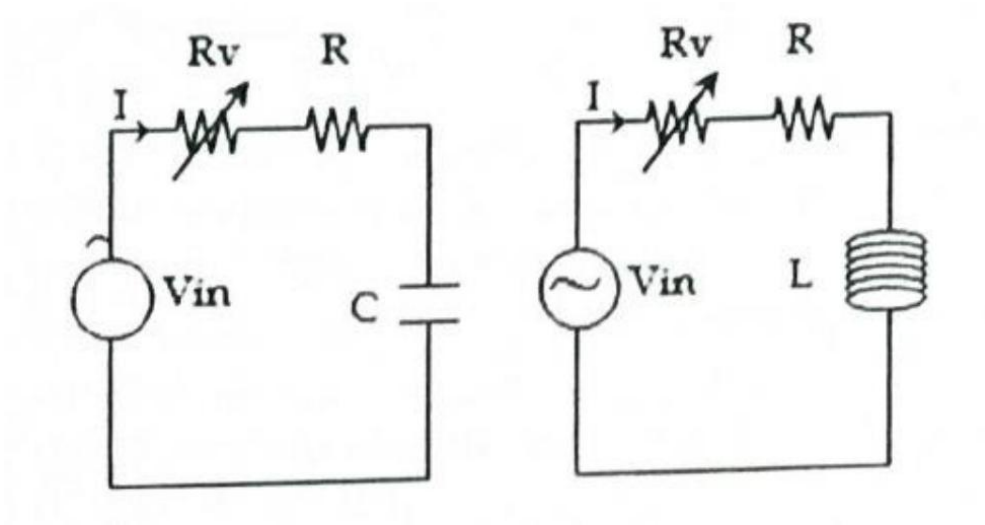


Figure 1. AC circuits: RC circuit on the left and RL circuit on the right

Capacitor

An RC circuit is a series circuit containing a resistor and a capacitor connected to a current or voltage source.

$$Xc = \frac{1}{(2\pi fC)} \qquad (1)$$

f = frequency of the applied voltage;
C = capacitance.

Inductor

An RL circuit consists of a resistor and an inductor connected to a current or voltage source.

$$X_l = 2\pi fL \qquad (2)$$

f = frequency of the applied voltage;
L = inductance.

C. EXPERIMENTAL METHOD

A. Apparatus and materials

No.	Apparatus or material	Quantity
1	Digital multimeter	1
2	Analog multimeter	1
3	Resistors	2
4	Connecting leads	As required
5	RL and RC circuit board	1
6	DC voltage source	As required
7	Capacitors	As required
8	Inductors	As required
9	Slide-wire rheostats	As required

B. Experimental procedure

- **RL circuit**
  1. Assemble the series RL circuit as illustrated.
  2. Set the power supply to AC at a selected voltage.
  3. Measure V_r, V_l, and the current I.
  4. Determine X_l for the circuit, then determine L using Equation (2).
  5. Repeat the measurements using different values of R and L.
  6. Change the input voltage V_{in} from AC to DC.
- **RC circuit**
  1. Assemble the series RC circuit as illustrated.
  2. Set the power supply to AC at a selected voltage.
  3. Measure V_r, V_C, and the current I.
  4. Determine X_C for the circuit, then determine C using Equation (1).
  5. Repeat the measurements using different values of R and C.
  6. Change the input voltage V_{in} from AC to DC.

C. Data tables

- **RL circuit**

Trial	$V_r \pm \Delta V$	$V_l \pm \Delta V$	$I \pm \Delta I$	$X_l = V_l/I$
1				
2				

- **RC Circuit**

Trial	$V_r \pm \Delta V$	$V_C \pm \Delta V$	$I \pm \Delta I$	$X_C = V_C/I$
1				
2				

L6 MAGNETIC FIELD

A. EXPERIMENTAL OBJECTIVES

1. Describe Lenz's law in electromagnetic induction.
2. Describe the relationship between a change in magnetic flux and the direction of the induced current.
3. Describe the process of self-induction.
4. Describe the force arising from an electric field on a wire carrying DC current.
5. Describe the force between two current-carrying wires.

B. THEORETICAL BACKGROUND

Lenz's law provides an alternative method for determining the direction of an induced current: the induced emf and current are directed so as to oppose the change that produces them. Faraday's law states that a change in magnetic flux through a coil induces an electromotive force (emf) proportional to the rate of change of flux. The induced emf depends on how rapidly the flux changes, rather than on the instantaneous flux itself.

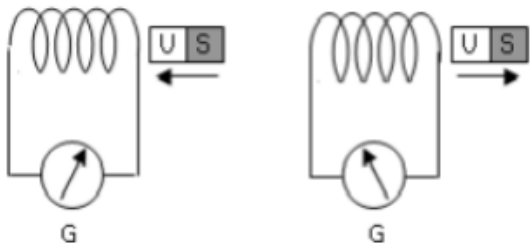


Figure 1. A magnet approaching and receding from a coil

Figure labels: U = north pole;
S = south pole.

The source describes magnetic induction as the magnetic field produced by an electric current flowing through a conductor. It uses the example of a compass placed parallel to a conductor: when current flows, the compass needle deflects; reversing the current reverses the deflection.

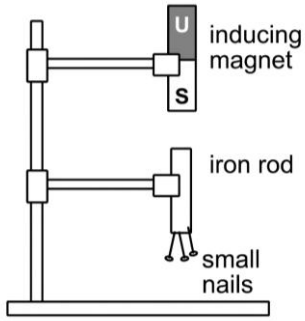


Figure 2. Magnetic induction

An electric current produces a magnetic field around the wire carrying it. When current is passed through a conductor, the space around it is altered. This can be detected indirectly, for example by the deflection of a magnetic needle, as in Oersted's experiment.

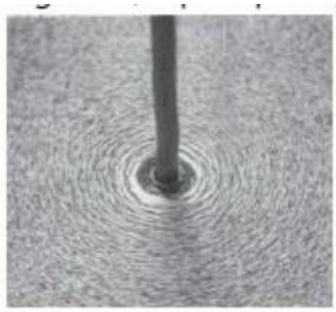
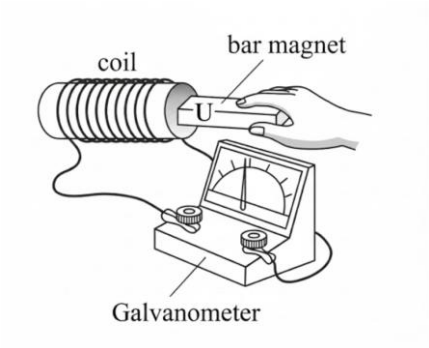


Figure 3. Current-carrying wire

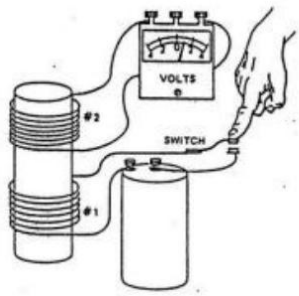
The magnetic Lorentz force is the force exerted by a magnetic field on a current-carrying wire. Its direction is perpendicular to both the current I and the magnetic induction B. Its magnitude depends on the current and the magnetic field.

C. EXPERIMENTAL METHOD

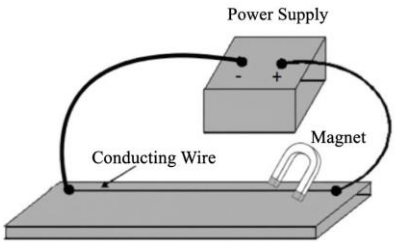
A. Experimental arrangements



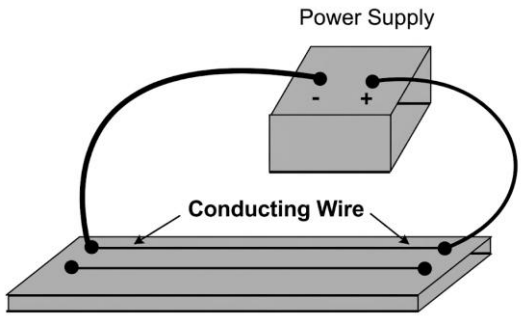
a. Lenz's law experiment



b. Experiment labeled self-induction in the source



c. Single current-carrying wire experiment



d. Parallel current-carrying wires experiment

B. Apparatus and materials

No.	Apparatus or material	Quantity
1	Coil kit	1
2	Magnet kit	1
3	Galvanometer	1
4	Batteries	3
5	Connecting leads	4
6	Wires	4
7	Iron rods	2

C. Experimental procedure

a. Lenz's law experiment

1. Assemble the apparatus as illustrated to test Lenz's law.
2. Connect the coil to the galvanometer.
3. Move the magnet to produce induction.
4. Observe the direction of the galvanometer deflection as the magnet is inserted into and withdrawn from the coil.

b. Self induction experiment

1. Assemble the apparatus as shown in the source diagram for testing Lenz's law.
2. Connect the first coil to the galvanometer.
3. Connect the second coil to a DC supply.
4. Insert a metal rod through both coils.
5. Open and close the circuit connected to the DC supply.
6. Observe the direction of the galvanometer deflection.
7. *Translator's note: Although labeled "self-induction," this two-coil arrangement demonstrates mutual induction. The source heading is retained.*

c. Single current carrying wire experiment

1. Connect the wire to a DC voltage source as illustrated.
2. Position the horseshoe magnet so that the current-carrying wire lies between its poles.
3. Observe the motion of the wire.

d. Parallel current carrying wires experiment

1. Arrange two wires parallel to one another and connect them to a DC voltage source as illustrated.
2. Observe the interaction between the two conducting wires.

01 LIGHT REFLECTION

A. EXPERIMENTAL OBJECTIVES

1. Verify the laws of reflection at a plane surface: the angle of incidence equals the angle of reflection, and the object distance equals the image distance.
2. Determine the focal length of a concave mirror.
3. Determine the characteristics of the image formed by a concave mirror in the experiment.

B. THEORETICAL BACKGROUND

When a beam of light strikes a surface, several outcomes are possible, one of which is reflection. A surface that reflects all, or nearly 100%, of the incident light is called a mirror. Reflection obeys the following laws, referred to as Snellius's laws in the source:

1. The incident ray, reflected ray, and normal all lie in the same plane.
2. The angle of incidence equals the angle of reflection.

A. Reflection at a plane mirror

When an object, such as a pin, is placed in front of a plane mirror, its image is visible in the mirror. Light appears to come from this image, although it actually travels from the object, reflects at the mirror, and reaches the eye.

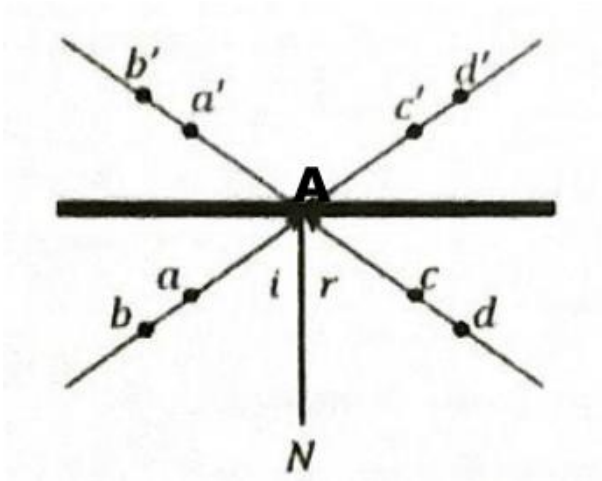


Figure 1. Equal angles of incidence and reflection at a plane mirror

The apparent direction of the light can be located using two pins, a and b. The line through them meets the mirror at A. Rays associated with pins c and d must meet this same point. The source identifies ab as the incident ray and cd as the reflected ray. By constructing the normal N at A, the angle of incidence i and angle of reflection r can be measured and their relationship investigated.

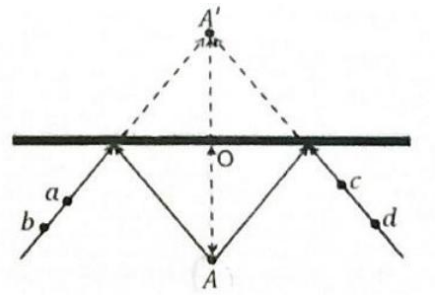


Figure 2. Equality of object and image distances at a plane mirror

A pin A is placed in front of the mirror, where its image A′ is visible. The lines defined by pins a, b, c, and d are extended to locate A′. Constructing AO from the object to the mirror and A′O from the mirror to the image allows these distances to be compared.

B. Reflection at a concave mirror

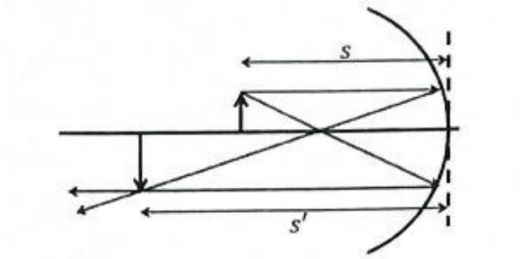


Figure 3. Reflection at a concave mirror

The object distance, image distance, and focal length are related by:

$$\frac{1}{f} = \frac{1}{s} = \frac{1}{s\prime} \qquad (1)$$

f = focal length;
s = object distance;
s′ = image distance.

C. EXPERIMENTAL METHOD

A. Apparatus and Materials

No.	Apparatus or material	Quantity
1	Optical bench	1
2	Plane mirror	1
3	Concave mirror	1
4	Ruler	1
5	Protractor	1
6	Screen	1
7	Candle and matches	1 set
8	Pins	As required
9	Cork board	1
10	Plain white paper	As required

B. Experimental procedure

❖ **Plane mirror with equal angles of incidence and reflection**

1. Place a sheet of paper on the cork board.
2. Choose an angle of incidence i.
3. Draw the mirror line, the normal N, and the incident-ray line at the selected angle, as illustrated in Figure 1(a) in the source.
4. Insert pins a and b along the incident-ray line.
5. Place the plane mirror with its reflecting surface on the mirror line.
6. Look from the other side so that the images a′ and b′ are visible in the mirror.
7. Insert pins c and d so that a′, b′, c, and d appear in one straight line.
8. Draw a straight line through c and d and extend it to the mirror line.
9. Measure the angle of reflection r with a protractor.
10. Repeat using at least five different angles of incidence.

❖ **Plane mirror with equal object and image distances**

1. Place a sheet of paper on the cork board.
2. Choose the object distance AO.
3. Draw the mirror line and mark the object position according to the selected distance, as in the source's Figure 1(b).
4. Insert a pin at A.
5. Insert pin a at an arbitrary position.
6. Insert pin b so that a and the image A′ appear aligned.
7. Repeat the corresponding alignment steps for pins c and d on the other side.
8. Extend lines ab and cd behind the mirror until they intersect at the image position A′.
9. Measure the image distance A′O using a ruler.
10. Repeat using at least five different object distances.

❖ **Concave Mirror**

1. Light the candle to serve as the object.
2. Align the screen, object, and mirror on the optical bench.
3. Set the object-to-mirror distance s.
4. Adjust the screen-to-mirror distance until a clear image is obtained.
5. Measure the screen-to-mirror distance s′ using a ruler.
6. Repeat each measurement at least three times.
7. Use at least five different object-to-mirror distances.

C. Data Tables

Tabulate the plane-mirror measurements. Determine the concave-mirror focal length using Equation (1), and record your results in the tables below.

Table 1 Equal angles of incidence and reflection

Trial	(i ± Δi)°	(r ± Δr)°
1		
2		
3		
4		
5		

Table 2 Equal object and image distances

Trial	(AO ± ΔAO) cm	(A′O ± ΔA′O) cm
1		
2		
3		
4		
5		

Table 3 Concave mirror focal length

Trial	(s ± Δs) cm	(s′ ± Δs′) cm	Image characteristics
1			
2			
3			
4			
5			

O2 LIGHT REFRACTION

A. EXPERIMENTAL OBJECTIVES

1. Verify Snell's law of refraction.
2. Determine the refractive indices of a semicircular glass block, a parallel-sided glass slab, and a prism.
3. Determine the lateral displacement of a ray through a parallel-sided glass slab.
4. Determine the minimum deviation angle of a prism.

B. THEORETICAL BACKGROUND

Snell's law of refraction

$$n = \frac{\sin i}{\sin r}$$

n = relative refractive index;
i = angle of incidence;
r = angle of refraction.

Refraction through a semicircular glass block

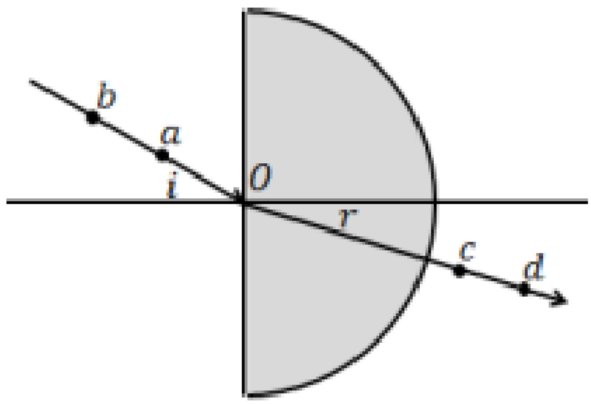


Figure 1. Refraction through a semicircular glass block

Refraction through a parallel sided glass slab

$$t = \frac{l \sin(i_1 - r_1)}{\cos r_1}$$

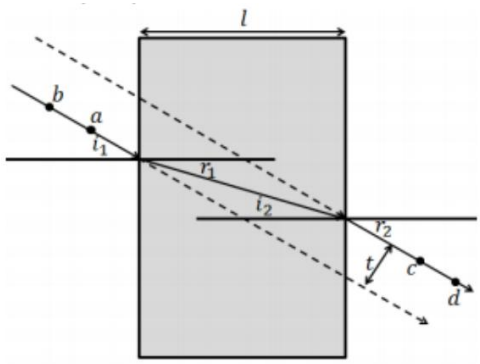


Figure 2. Refraction through a parallel-sided glass slab

Refraction through a prism

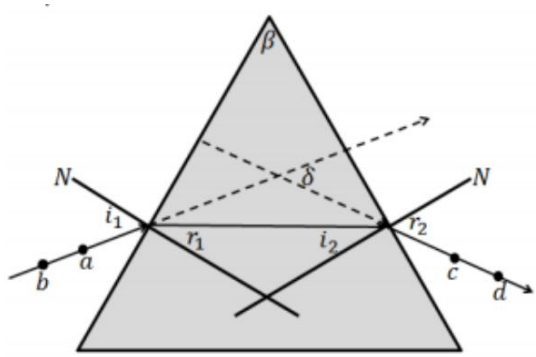


Figure 3. Refraction through a prism

The source prints the following relations:

$$\delta = i_1 + r_2 = \beta$$

$$n_1 = \sin[\tfrac{1}{2}(\beta + \delta_m)] = n_2 \sin(\tfrac{1}{2}\beta)$$

C. EXPERIMENTAL METHOD

A. Apparatus and materials

No.	Apparatus or material	Quantity
1	Semicircular glass block	Not specified
2	Parallel-sided glass slab	Not specified
3	60° prism	Not specified
4	Pins	Not specified
5	Protractor	Not specified
6	Ruler	Not specified
7	White paper	Not specified
8	Cork board	Not specified
9	Pencil	Not specified
10	Laser	Not specified

B. Experimental procedure

❖ Semicircular glass block

1. Trace a semicircle matching the shape of the glass block.
2. Draw a normal to its flat surface.
3. Choose the angle of incidence i and draw the incident-ray line.
4. Place the paper and glass block on the cork board.
5. Switch on the laser and align its beam with the incident-ray line.
6. Use pins to mark the incident ray and the refracted ray emerging from the glass.
7. Draw additional lines to trace the refracted path on the paper, as in Figure 1.
8. Measure the angle of refraction r.
9. Repeat the experiment to obtain accurate and reliable data

❖ Parallel sided glass slab

1. Trace a rectangle matching the shape of the glass slab.
2. Draw a normal to one surface.
3. Choose i_1 and draw the incident-ray line.
4. Place the paper and glass slab on the cork board.
5. Switch on the laser and align its beam with the incident-ray line.
6. Use pins to mark the incident ray and the refracted ray emerging from the slab.
7. Draw additional lines to trace the refracted path on the paper, as in Figure 2.
8. Draw a second normal at the other surface.
9. Measure r_1, the second angle of incidence i_2, the second angle of refraction r_2, and the lateral displacement t.
10. Repeat the experiment to obtain accurate and reliable data.

❖ Prism

1. Trace a triangle matching the shape of the prism.
2. Draw a normal to one surface.
3. Choose i_1 and draw the incident-ray line.
4. Place the paper and prism on the cork board.
5. Switch on the laser and align its beam with the incident-ray line.
6. Use pins to mark the incident ray and the refracted ray emerging from the prism.
7. Draw additional lines to trace the refracted path on the paper, as in Figure 3.
8. Draw a second normal at the other surface.
9. Measure r_1, the second angle of incidence i_2, and the second angle of refraction r_2.
10. Measure the deviation angle δ and the prism angle β.
11. Repeat the experiment to obtain accurate and reliable data.

C. Data Tables

❖ Semicircular glass block

Trial	$(i \pm \Delta i)°$	$(r \pm \Delta r)°$
1		
2		
3		
4		
5		

❖ Parallel sided glass slab

Trial	$(i_1 \pm \Delta i)°$	$(r_1 \pm \Delta r)°$	$(i_2 \pm \Delta i)°$	$(r_2 \pm \Delta r)°$	$t \pm \Delta t$
1					
2					
3					
4					
5					

❖ Prism

Trial	$(i_1 \pm \Delta i)°$	$(r_1 \pm \Delta r)°$	$(i_2 \pm \Delta i)°$	$(r_2 \pm \Delta r)°$	$(\delta \pm \Delta\delta)°$	$(\beta \pm \Delta\beta)°$
1						
2						
3						
4						
5						

O3 LENS

A. EXPERIMENTAL OBJECTIVES

1. Determine the effect of object distance on image distance for a positive lens.
2. Determine the effect of object distance on image distance for a negative lens.
3. Determine the focal length of a positive lens from experimental data.
4. Determine the focal length of a negative lens from experimental data.

B. THEORETICAL BACKGROUND

a. Convex lens

A convex lens focuses incident light and is also called a positive lens. It is positive because it causes light rays to converge.

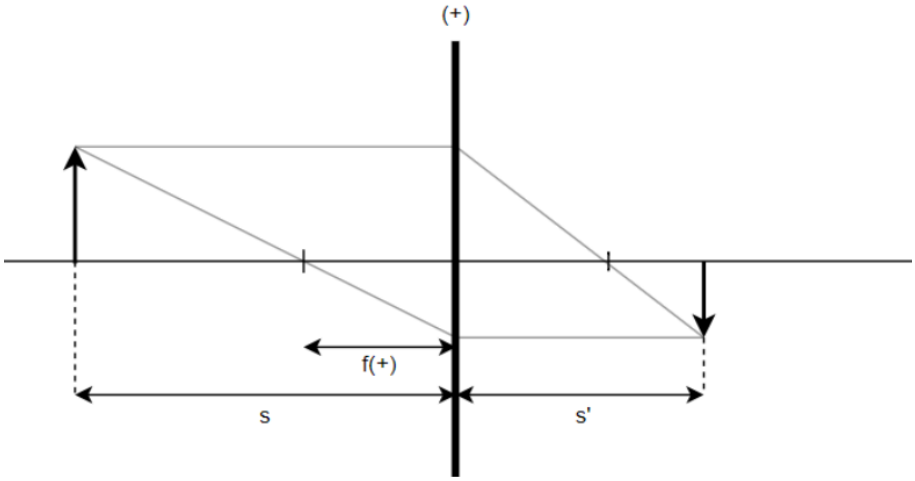


Figure 1. Convex lens

The focal length of a convex lens can be determined from:

$$\frac{1}{f_{(+)}} = \frac{1}{s} + \frac{1}{s\prime}$$

f = focal length of the convex lens (cm);
s = object distance (cm);
s′ = image distance (cm).

Convex lenses are used to correct hyperopia (farsightedness), and in magnifying glasses, telescopes, microscopes, periscopes, projectors, and other optical devices.

b. Concave lens

A concave lens spreads incident light and is also called a negative lens. It is negative because it causes light rays to diverge.

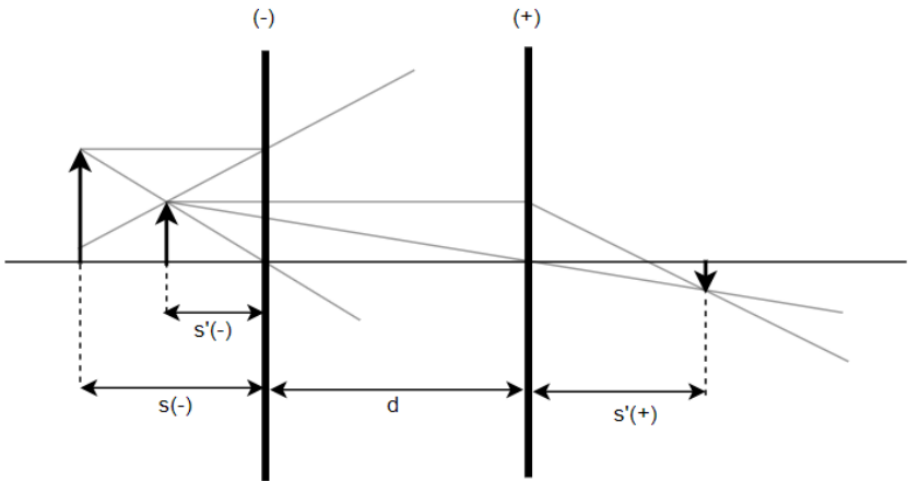


Figure 2. Concave lens

The source gives the following relation for the focal length:

$$\frac{1}{f_{(-)}} = \frac{1}{s_{(-)}} + \frac{1}{s\prime_{(-)}}$$

Because some variables in this relation cannot be measured directly, a convex lens is used as an auxiliary lens together with the following equation:

$$\frac{1}{f_{(+)}} = \frac{1}{(s\prime_{(-)} + d)} + \frac{1}{s\prime_{(+)}}$$

$f_{(-)}$ = concave-lens focal length (cm);
$s_{(-)}$ = object distance relative to the concave lens (cm);
$s'_{(-)}$ = image distance relative to the concave lens (cm);
d = separation of the two lenses (cm);
$f_{(+)}$ = positive-lens focal length (cm);
$s'_{(+)}$ = image distance relative to the positive lens (cm).

Concave lenses are used to correct myopia (nearsightedness) by adjusting how incoming light is focused in the eye.

C. EXPERIMENTAL METHOD

A. Apparatus and materials

No.	Apparatus or material	Quantity
1	Optical bench	1
2	Convex lens	1
3	Concave lens	1
4	Candle	1
5	Screen	1

B. Experimental procedure

❖ Convex lens

1. Assemble the apparatus as in Figure 1.
2. Move the lens and screen until a clear, sharp image is formed on the screen.
3. Record the object-to-lens distance and screen-to-lens distance.
4. Calculate the focal length.
5. Repeat steps 2–4 while varying the manipulated variable.

❖ Concave lens

1. Assemble the apparatus as in Figure 2.
2. Move the lenses and screen until a clear, sharp image is formed on the screen.
3. Record the object-to-lens distance and screen-to-lens distance.
4. Calculate the focal length.
5. Repeat steps 2–4 while varying the manipulated variable.

C. Data Tables

Tabulate your experimental results for each experiment.

Table 1 Convex lens measurements

Trial	s	s′
1		
2		
3		
4		
5		

Table 2 Concave lens measurements

Trial	$f_{(+)}$	d	$s'_{(+)}$	$s_{(-)}$
1				
2				
3				
4				
5				

04 OPTICAL INSTRUMENTS

A. EXPERIMENTAL OBJECTIVES

1. Determine magnification in a magnifying glass and a microscope.
2. Determine the focal length of a camera lens.
3. Design demonstrations of a magnifying glass, camera, and microscope, including the characteristics of their images.

B. THEORETICAL BACKGROUND

Optical instruments use optical components such as mirrors, lenses, prisms, and optical fibers. They operate using the principles of reflection and refraction.

a. Magnifying glass

A magnifying glass is a convex lens with a short focal length. The object to be magnified is placed within the focal length, so that its distance from the lens is smaller than the focal length. The resulting image is upright, virtual, and magnified.

b. Lenses

A lens is a transparent optical element bounded by two curved surfaces or by one curved and one plane surface. Types include convex and concave lenses. A convex or converging lens is thicker at its center than at its edges and brings rays together. A concave or diverging lens is thinner at its center than at its edges and spreads rays apart. A concave lens is also called a negative lens. Optical instruments produce magnified images. Linear magnification is given in the source by:

$$M_i = s'/s$$

M_i = linear magnification (dimensionless);
s = object distance (m);
s′ = image distance (m).

The angular-magnification equation is printed as:

$$M_a = PP\,[1/(s' + d) + 1/f - d/\{f(-s' + d)\}]$$

M_a = angular magnification (dimensionless);
PP = near-point distance of the eye (m);
s′ = image distance (m);
s = object distance (m);
d = eye-to-lens distance (m);
f = focal length (m).

The focal length of a lens can be determined using:

$$1/f = 1/s + 1/s'$$

f = focal length (m);
s = object distance (m);
s′ = image distance (m).

C. EXPERIMENTAL METHOD

a. Apparatus and materials

The apparatus and materials are: one precision-rail set, clamped supports, a candle holder, a screen, a candle cover, a positive lens, a negative lens, a candle, and matches.

b. Experimental procedure

❖ **Magnifying glass**

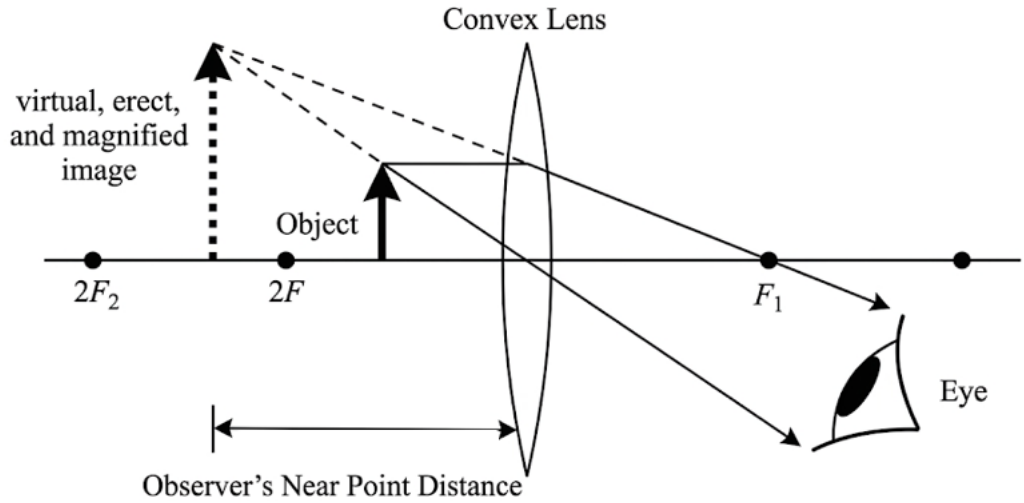


Figure 1. Image formation by a magnifying glass

1. Assemble the apparatus as shown in Figure 1.
2. Determine the observer's near-point distance PP.
3. Draw a picture or write a character, such as the letter A, on paper to serve as the object.
4. Align the object, lens, and eye along the optical bench.
5. Look at the image of the object through the lens.
6. Adjust the object-to-lens distance s so that the image lies at the near point PP.
7. Measure the eye-to-lens distance d.
8. Repeat the experiment at least five times.
9. Use at least three different object-to-lens distances.

❖ **Camera**

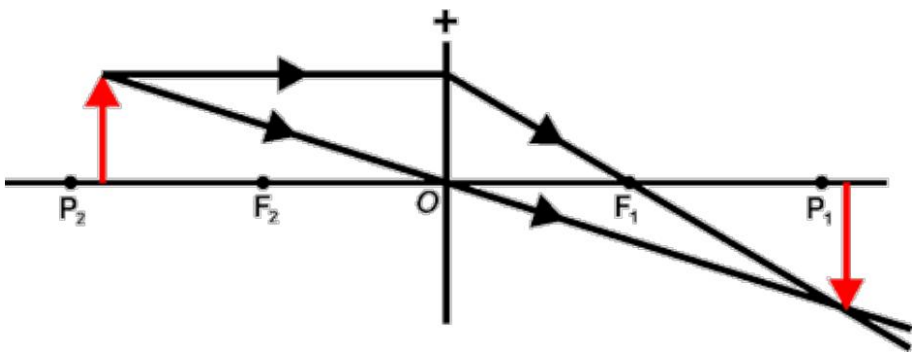


Figure 2. Image formation by a camera

1. Assemble the apparatus as shown in Figure 2.
2. Light the candle to serve as the object.
3. Align the object, lens, and screen along the optical bench.
4. Set the object-to-lens distance s.
5. Adjust the screen-to-lens distance until a clear image is obtained.
6. Measure the screen-to-lens distance s′ using a ruler.
7. Repeat the experiment at least three times.
8. Use at least three different object-to-lens distances.

❖ **Microscope**

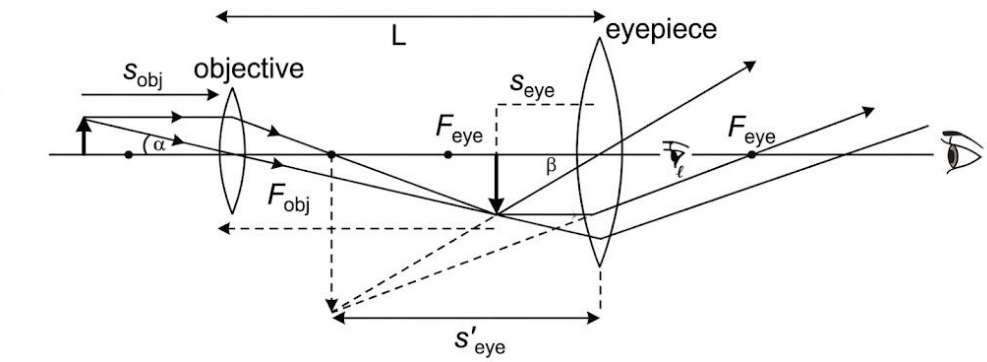


Figure 3. Image formation by a microscope

1. Assemble the apparatus as shown in Figure 3.
2. Determine the observer's near-point distance PP.
3. Light the candle and position it as the object in front of the objective lens.
4. Align the object, objective lens, and screen along the optical bench.
5. Set the object-to-objective distance $s_{o\beta}$.
6. Adjust the screen-to-objective distance until a clear image is obtained.
7. Measure the screen (image)-to-objective distance $s'_{o\beta}$ using a ruler.
8. Position the eyepiece so that the object, objective lens, screen, and eyepiece are aligned along the optical bench.
9. Remove the screen so that it does not obstruct the light.
10. Look at the image through the eyepiece.
11. Set the eye-to-eyepiece distance d to a very small value.
12. Adjust the eyepiece-to-objective separation x until the image lies at the near point.
13. Repeat the experiment at least five times with x held constant.

D. Assignment

Tabulate the experimental results for each experiment.

Table 1 Magnifying glass measurements

Trial	$d \pm \Delta d$	$s \pm \Delta s$	Image characteristics
1			
2			
3			
4			
5			

Table 2 Camera measurements

Trial	$s \pm \Delta s$	$s' \pm \Delta s'$	Image characteristics
1			
2			
3			
4			
5			

Table 3 Microscope measurements

Trial	$s_{o\beta} \pm \Delta s$	$s'_{o\beta} \pm \Delta s$	$x \pm \Delta x$	$d \pm \Delta d$	Image characteristics
1					
2					
3					
4					
5					

O5 DIFFRACTION GRATNG

A. EXPERIMENTAL OBJECTIVES

1. Determine the wavelength of colored laser light.
2. Determine the frequency of colored laser light.

B. THEORETICAL BACKGROUND

Diffraction is the spreading of a wave as it passes through a narrow opening or around a sharp edge. It is a characteristic of wave behavior. In a classical particle description, a freely moving particle passing through an opening would not change direction. A diffraction grating is an instrument for analyzing light sources. It consists of many equally spaced parallel slits and may contain thousands of lines per centimeter. The slit spacing, or grating constant d, is the reciprocal of the number of lines per unit length N: $d = 1/N$.

The equations used for the diffraction grating are:

$$d \sin \theta = n\lambda$$

$$d(P/L) = n\lambda \qquad (1)$$

d = slit spacing (m);
n = diffraction order;
λ = wavelength (m);
P = distance from the central bright fringe to the nth-order bright fringe (m);
L = distance from the grating to the screen (m).

The speed of light is related to frequency and wavelength by:

$$c = f\lambda \qquad (2)$$

c = speed of light (m/s);
f = frequency (Hz).

C. EXPERIMENTAL METHOD

a. Apparatus and materials

One diffraction grating, three lasers, a screen, and a ruler.

b. Experimental procedure

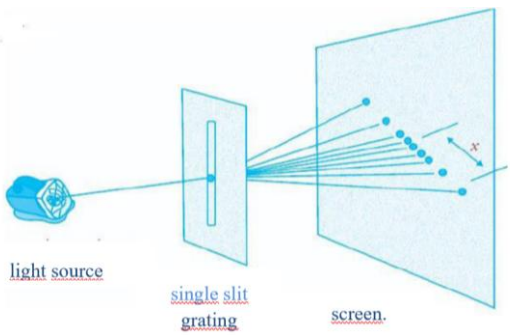


Figure 1. Diffraction-grating experiment

1. Assemble the apparatus as shown in Figure 1.
2. Observe the light beam from behind the diffraction grating.
3. Set the grating-to-screen distance L.
4. Measure P for the first-order bright fringe.
5. Repeat the measurement of P at least three times.
6. Use at least five different grating-to-screen distances.
7. Repeat using at least three different gratings or grating spacings.
8. Repeat the procedure for different light colors: red, green, and blue.

c. Data tables

Table 1 Red light measurements

Trial	d ± Δd	Order n	L ± ΔL	P ± ΔP
1				
2				
3				
4				
5				

Table 2 Green light measurements

Trial	d ± Δd	Order n	L ± ΔL	P ± ΔP
1				
2				
3				
4				
5				

Table 3 Blue light measurements

Trial	d ± Δd	Order n	L ± ΔL	P ± ΔP
1				
2				
3				
4				
5				

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