A LABORATORY MANUAL OF
EXPERIMENTS IN PHYSICS

BY

LEONARD ROSE INGERSOLL
Professor of Physics, University of Wisconsin

AND

MILES JAY MARTIN
Associate Professor of Physics, Milwaukee Extension Center, University of Wisconsin

THIRD EDITION
SECOND IMPRESSION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK AND LONDON
1932

PREFACE

In the preparation of the present edition of this manual the book in its previous form has been completely rewritten and almost forty per cent of new material has been added. All the best of the former experiments have been retained, however, with only relatively minor changes in procedure so that laboratories accustomed to the former edition will experience no inconvenience with the present one; but most of the descriptions have been recast. A particular feature is the brief digest of the underlying theory which accompanies each experiment and serves to bridge the gap between formal class work and laboratory exercises. The instructions are somewhat more specific and clear-cut than formerly, but we have kept continually in mind the dangers of being over-specific. The aim has been to strike a satisfactory mean between the one extreme of giving directions so sketchy that the student is unable to make headway, and the other of providing cookbook-like instructions which leave nothing to his ingenuity.

Since the book is designed for use with both general and technical courses, it will be found to contain a rather wide variety of experiments ranging from relatively simple ones to those of a more exacting nature. Nearly one-fourth of the experiments are new, and a number of these make use of improved forms of apparatus which have recently been developed and put on the market. We feel sure that these new experiments, as a whole, will come to be regarded at least as highly as any of the older ones. In general it will be found that they are slightly more involved than the others, but they are usually divided into parts so that the instructor can make a suitable selection for a particular class of students. In the same way a choice may be made of the questions and problems. The occasional question marked as difficult by an asterisk may serve to stimulate the outstanding student.

It is not easy to avoid a certain amount of local color in a manual. This has been reduced to a minimum, but in those few cases where it has been necessary we have frankly specified that certain instructions are for University of Wisconsin students. To adapt the book to the needs of the average user, almost all of the apparatus called for is standard and each experiment is accompanied by a statement of the apparatus requirements. In the few instances where special equipment or assembly is required, we have tried to make the arrangement clear so that it can be duplicated if desired. All the new experiments have been tested with many groups of students and we hope that this has resulted in the elimination of inaccuracies and ambiguities, but we shall be glad to have any such as remain called to our attention.

We wish to acknowledge our indebtedness to the following apparatus and instrument companies for the use of illustrations or other material: Central Scientific Company, Gaertner Scientific Corporation, General Electric Company, Leeds and Northrup, and the W. M. Welch Scientific Company. We also wish to express our thanks to the staff of physical laboratory instructors of the University of Wisconsin, and particularly to Dr. T. A. Rouse and Mr. L. T. Earls, for continuous assistance during the preparation of the book.

L. R. Ingersoll.
M. J. Martin.

Madison, Wisconsin,
Milwaukee, Wisconsin,
July, 1932.

CONTENTS

A LABORATORY MANUAL OF
EXPERIMENTS IN PHYSICS

INTRODUCTION

1. Initial Instructions.—Laboratory work in physics is designed to familiarize the student with the fundamental laws and principles of the subject and to acquaint him with the methods of making physical measurements. The success of experimental work depends upon the exercise of thoroughness and care and upon the originality and ingenuity of the experimenter. It is quite possible—and, in fact, frequently the case—that two students will perform the same experiment in the same way with identical apparatus and yet obtain widely different results, due to the fact that one exercises care and originality while the other merely follows the instructions mechanically. So while specific directions are given for each experiment, it cannot be too strongly impressed on the student that satisfactory experimental work means more than the mere following of such instructions. It means that the student should at each stage of the procedure know just *what* he is doing and *why* he is doing it.

Accordingly, before beginning an experiment the student is asked to read carefully through the instructions and, as far as possible, to *familiarize himself with the theory.* In many cases it will be desirable to look up the subject in a general text. Descriptions of particular instruments, special technique, etc., will be found in Appendix I and should always be read when they apply to the experiment.

2. Measurements. Data.—All measurements are to be recorded as made and incorporated as a part of the finished report. At the University of Wisconsin data are taken on sheets of yellow paper of special size (7¼ by 10 in.). If, as is customary, two students work together at an experiment, the data sheets are to be made in triplicate, using two carbons. This gives a copy for each student and one which is to be left with the instructor. If the student works alone, only a single carbon is to be made.

The data sheet should contain *all* the measurements and must never be altered once the observations have been completed. Erasures should never be made on the data sheet; if a mistake is made, cancel the wrong part with a line. In many experiments it will be found useful to rule the paper so that the data may be taken down in tabulated form. Each student should take his turn at reading the instruments, and care should be taken to state the units in which the measurements are made. Also *record the date on which each set of observations is taken.* At the conclusion of the experimental work the instructor will initial the data sheets if the work has been satisfactory and file his copy. Unfinished data must not be taken from the laboratory.

While many of the measurements made in the physical laboratory are within the scope of everyday experience, *e.g.*, the use of a rule in measuring lengths, there are certain requirements in scientific work which may be new to the student but with which he must become acquainted at the earliest opportunity. The first of these is the number of determinations to be made in any particular measurement. It is a fundamental law of laboratory work that a *single* measurement is of little value because of the liability not only to gross mistakes but also to smaller errors. Accordingly it is customary to repeat all measurements so that the total number of observations of a particular quantity is seldom less than 3 and in some cases even 10 or more. The average of these readings is obviously of a greater probable accuracy than any one could possibly be alone. The number of readings to be taken is usually specified in the earlier experiments, but it is expected that the student will soon accustom himself to this requirement and will always take his measurements in sets of three or more, whether this is explicitly specified or not.

Requirements of accuracy demand that each measurement be made as carefully as possible, and to fulfill this requirement it is universal practice in physical measurements to estimate the reading of a scale to tenths of the smallest division. Thus if a scale is divided into millimeters, as is the ordinary meter stick, the reading will be expressed in tenths of a millimeter, *e.g.*, 4.3 mm., 27.42 cm. In case the reading falls exactly on a scale division, the tenths are expressed by 0, *e.g.*, 6.0 mm., 48.50 cm.

3. Reports.—The final report on the experiment (at Wisconsin on 7¼ by 10-in. white sheets) should embody, in addition to the data sheet:

1. Name and number of experiment. Name and number of student and partner.
2. Object of the experiment (to be stated in the student's own words).
3. Apparatus used, with diagram; give numbers of apparatus when possible.
4. Description of how the experiment was performed.
5. Method of deducing results from original data.
6. Summary of results; be sure to specify units and, where possible, place side by side with the results standard values as given in physical tables, for purposes of comparison.
7. Curves, if required.
8. Physical interpretation of results and answers to questions.
9. It is also frequently possible and profitable to include a discussion of sources of error and their elimination.

When an experiment has been completed the student should talk the matter over with the instructor in order that any difficulties may be cleared up. Later the instructor will make a more careful survey of the report. If returned to the student for correction, such corrections should be made at once. Good laboratory work involves writing up and completing the experiment as soon as possible after taking the data. *In general, full credit cannot be allowed for experiments in which there is unnecessary delay in the submission of the completed report.*

The answers to the questions on each experiment constitute one of the most important parts of the finished work. These should in every case be written, generally at the end of the report. Also it is wise, as a rule, to sketch out the answers on the data sheet and talk them over with the instructor at the time the measurements are completed. Questions or problems marked with an asterisk are more difficult than the others and, needless to say, are for the ambitious student who wants to make his work as complete as possible.

4. Computations. Significant Figures.—All but the simplest computations should be made with either slide rule or logarithms. Simple log tables will be found in Appendix II, and half an hour's study of the instructions preceding them should render it possible for even the student without previous experience with logarithms to use them.

When an equation involving a number of quantities is to be solved, write the equation first in symbolic form; then rewrite it, substituting experimentally determined quantities; finally write it a third time, reducing all quantities to simple numbers of one and two digits and powers of 10. This enables one to locate the decimal point readily and facilitates checking over computations. *Do not fail to state the units in which the result is obtained.*

No matter to how many decimal places the computation may be carried, the accuracy of the result cannot exceed that of the data. If three successive measurements with a meter stick give 48.25, 48.23, 48.22 cm., as the length of a certain rod, the average might be expressed as 48.2333333 cm. But as the meter stick is divided only to 0.1 cm. and the next figure is obtained by estimating tenths, the result should not be expressed to more than two, or at most three, decimals. By the term "significant figures" is meant those figures in a result which are trustworthy and have some significance. Obviously, the figures after the third decimal place in the length just mentioned are of no value and so are not significant figures. The position of the decimal point in no way affects the number of these figures; this number is determined entirely by the accuracy of the data. Suppose three significant figures are to be retained in the following numbers: 1,763,298.23 and 0.0003628. Then they should be written 1,760,000 and 0.000363.

In ordinary laboratory work it is usually unnecessary to have more than four significant figures in the result, but the following rules may prove useful:

1. In addition and subtraction do not carry the result beyond the first column which contains a doubtful figure.

2. In multiplication and division the number of significant figures in the result should be one greater than the smallest number of trustworthy figures contained in any factor used in obtaining the result.

These rules give the number of significant figures which should appear in the result, the last figure being always in doubt; but, in computing, it is better to carry one more figure than they specify. The following examples illustrate the principles just mentioned:

$$4{,}567 + 1.48 + 0.0764 = 4{,}568.6$$
$$13.28 \times 2.06 = 27.36$$
$$0.0735 \times 0.002 = 0.00015$$
$$189{,}324{,}500 \times 66 = 12{,}500{,}000{,}000 = 125 \times 10^8$$

5. Errors.—Absolute accuracy is, of course, unattainable in laboratory measurements. Every result, no matter how carefully obtained, has a certain "probable error" which depends on the number of measurements, their concordance, and some other factors. It should be the aim of the student to make his measurements with the greatest accuracy attainable with the given apparatus; in no case, however—except by accident—will his results agree exactly with the true values of the quantities measured.

Errors are commonly listed as either *absolute* or *relative.* If a length of 400 cm. is measured as 398 cm., the absolute error is 2 cm., while the relative error is $2/400$ or 0.5 per cent. If quantities are to be added or subtracted, it is the actual or absolute error which is of importance; if multiplied or divided, the relative or percentage error. In the latter case the relative error of the separate quantities determines the error of the final result, and for this reason small quantities should be measured with special care to keep the percentage error low. This is particularly true when a quantity is squared or raised to some higher power, in which case the relative error of the result is multiplied by this power. Thus in experiments on torsion the radius of the wire appears raised to the fourth power. This means that if the wire is 1 mm. in diameter and the absolute error of its measurement is 0.01 mm., this relative error of 1 per cent causes an error of 4 per cent in the final result.

An indication of the trustworthiness of a result is given by the consistency of the individual measurements. If these show only a small variation or deviation from the mean value, the accuracy of the final result may be taken as correspondingly high. As an example consider the series of readings given in the column shown on page 6.

Readings, Centimeters	Deviations, Centimeters
17.304	0.047
17.483	0.132
17.266	0.085
17.325	0.026
17.379	0.028
5)86.757	5)0.318
17.3514	0.0636

The arithmetic average, 17.3514, is obtained as indicated. The deviation of each reading from the average is given in the second column. The average deviation is 0.0636 cm. This is frequently called the average error. In relative form it is 0.0636/17.3514 = 0.0035 or 0.35 per cent.

6. Averaging. Method of Differences.—Since experimental values involve errors, some averaging process is desirable in order to lessen the final error. A result which is based on a large number of readings is more accurate than one based on one or two readings. When several readings are taken separately, the most nearly correct value of the quantity is the ordinary arithmetic average. It is to be noted that this is used only *when the readings are wholly independent of each other.* For example, if several measurements are made of the diameter of a wire, the most dependable value to take would be the arithmetic mean of the individual determinations.

Under certain circumstances this method is not satisfactory. This may be seen from the following discussion: If the average width of a board on the floor of a room is desired, several methods may be followed. The obvious way would be to measure the total width of a certain number of boards and divide this total by the number of boards included. The result is dependent only on the two end readings; it would be more accurate if a number of readings were involved.

Another method which at first appears more accurate is to lay a scale across the floor, note the reading on the scale at the edge of each board, subtract these readings in order to find the width of each board, and then find the ordinary average of these differences.

In this case, however, the arithmetic average does not give the best result obtainable from the data. In order to see its failure let the successive readings on the scale be a, b, c, d, e, f, as illustrated in Fig. 1. These readings are steadily increasing across the scale. The width of the first board is then b-a; the width of the second is c-b; etc. If the arithmetic average be taken, we should add the differences and divide by their number:

$$\begin{array}{c} b-a \\ c-b \\ d-c \\ e-d \\ \underline{f-e} \\ f-a \end{array}$$

Thus when the successive differences are added, the intermediate readings are eliminated leaving only f-a. This is precisely the result obtained in the foregoing method and shows the final result to be dependent only on the end readings. The intermediate readings are therefore wholly useless and may be in error by any amount without influencing the result. Suppose, for instance, that a large error had been made in the second reading and that this reading is represented by b' instead of b. Obviously the observed width of the first board is b'-a and that of the second board is c-b', but the sum of the two differences is c-a just as before. Hence the reading at b' has no effect upon the result.

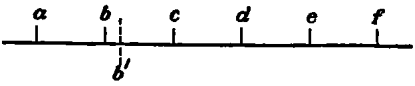

FIG. 1.—Illustration of "method of differences."

There is, however, a way of averaging—sometimes called the "method of differences"—which makes use of these intermediate readings. Divide the readings into two equal groups, a, b, c and d, e, f. Subtract the first reading in group A from the first in group B, *i.e.*, (d-a); then subtract the second in group A from the second in group B, *i.e.*, (e-b); etc. Thus:

$$\begin{array}{c} d-a \\ e-b \\ f-c \end{array}$$

Each of these differences represents three of the desired intervals. If the differences are added, no readings will be eliminated, and the sum will represent nine of the desired intervals. Finally, a single interval (in this example the width of one board) is found by dividing the total by the number of intervals represented. The effect of this method is to make each reading the beginning point or the end point of some difference (using in the example three differences with three boards in each) and thus make the final result depend upon all readings instead of only two.

As an illustration this method of averaging will be applied to the following data taken to determine the period of vibration of a certain pendulum:

Observation	Vibration	Time			Differences			
		h	m	s		vib.	m	s
1	0	2	35	50	Fifth-first..............	400	13	19
2	100		39	9	Sixth-second............	400	13	21
3	200		42	29	Seventh-third...........	400	13	21
4	300		45	48	Eighth-fourth...........	400	13	22
5	400		49	9				
6	500		52	30	Total................	1,600	53	23
7	600		55	50			or	
8	700		59	10			3,203$^{sec.}$	
					∴ Period is 3,203/1,600 = 2.002$^{sec.}$			

It is to be noted that this special method of averaging is to be used only when the average of a number of *successive differences* is desired. For all other cases the ordinary arithmetic average is satisfactory.

7. Plotting of Curves.—In the plotting and discussion of curves the following terms are frequently used:

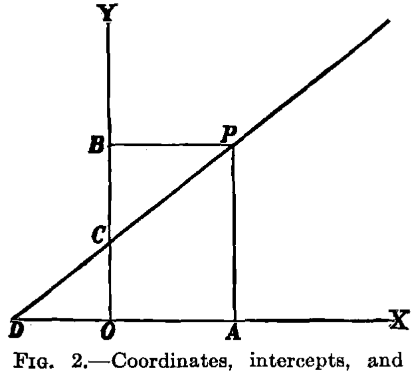

FIG. 2.—Coordinates, intercepts, and slope.

The *abscissa* is the distance *OA* (Fig. 2) measured along the horizontal line *OX*. This line is called the axis of abscissas or *X*-axis.

The *ordinate* is the distance *OB* measured along the vertical line *OY*, the axis of ordinates or *Y*-axis. These two distances *OA* and *OB* are called the *coordinates* of the point *P*.

The *origin* is the point O, the intersection of the two axes. This point is called the origin only when the magnitudes plotted on the two axes have their zero values at this point.

An *intercept* is the distance measured from the origin along one of the axes to the point at which the curve meets the axis. Thus OC is the Y-intercept and OD the X-intercept for the curve in Fig. 2.

The *slope* of a curve is a measure of the angle which the curve makes with the X-axis. It is the trigonometrical tangent of this angle; thus in the figure the slope is AP/DA.

The following general rules should be observed in plotting curves:

a. Choice of scales. Use, in general, only standard 15 by 20-cm. coordinate paper. Choose such scales that the curve will extend nearly the full length of the sheet in both directions, but make them convenient; *i.e.*, have each division equal to 1, 2, 4, 5, or 10, etc., units. The scales need not be the same for both axes. Label the main divisions, the numbers increasing from left to right and from bottom to top. It is customary to plot the independent variable as abscissa and the dependent as ordinate.

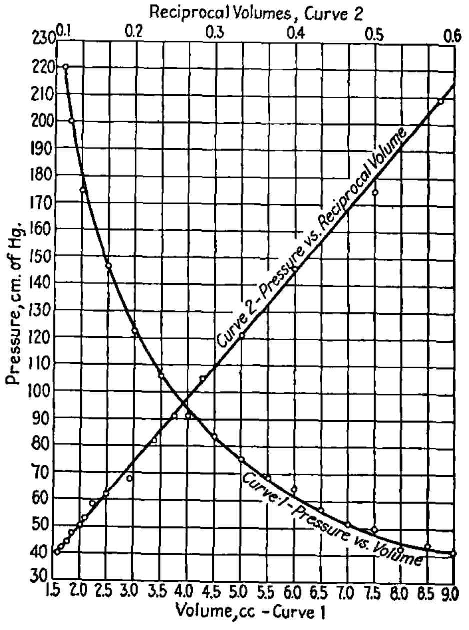

FIG. 3.—Typical graphs.

b. Plotting. Locate experimental points by small, sharp dots. Draw around each point a small circle in ink; crosses are also frequently used. Draw a smooth curve, first in pencil and then in ink, passing through (or near) as many of the points as possible, but do not make it irregular to get in all the points and do not draw the final line *through* the circles (note the way in which the curves in Fig. 3 are interrupted at the circles). The curve should indicate the average trend of the data.

It should never be merely a series of straight lines connecting the points.

c. Labeling curve and coordinates. Print the title of the curve and number of the experiment on the sheet, also your name. Along each axis label the coordinates, stating the *quantity* plotted and the *units* in which it is expressed (see Fig. 3). When two or more curves are on one sheet, use different colors of ink if possible for the different scales and corresponding curves, or else use dotted or broken lines.

d. Interpretation of curves. This means to state what physical law or conclusions may be drawn from such a curve. For instance, if a curve of distances covered by a falling body plotted against squares of the times should come out as a straight line passing through the origin, the conclusion would be that the space covered by a falling body is directly proportional to the square of the time.

8. Wisconsin Laboratory Rules.

1. Be punctual; habitual tardiness will be counted as absence.

2. Absences must be made up. If possible, this should be done under the student's own instructor. In any case, the student should be sure that the instructor enters the credit on his work card.

3. Follow the laboratory bulletin board.

4. Credit will not be given for experiments which have not been regularly assigned or for which the data sheets have not been initialed by an instructor. Full credit will not be allowed when there is unnecessary delay in submitting the completed report on the experiment.

5. *Under no circumstances may a student use data in the taking of which he has not had a part.* This is particularly applicable when a student is absent and his partner performs the experiment alone. Such data must not be used in any way by the absent student.

6. Students are asked not to move apparatus about the room without permission or to go behind the desk. Special cooperation is asked in keeping apparatus and laboratory in as good shape as possible.

7. The laboratory will close for the semester on the Saturday noon before final examinations. Not more than two experiments can be accepted during the last week save by permission of the laboratory director.

8. Occasional oral or written quizzes may be given on the laboratory work, and in the last period of the semester a final laboratory examination will be held.

I. MECHANICS

EXPERIMENT 1

The Rule

OBJECT: To become familiar with some of the principles of physical measurement through a simple experiment.

FOREWORD: All physical measurements from the simplest to the most complex depend on the same fundamental principles, certain of which will be illustrated here by the use of the ordinary rule. The measurement of distance is perhaps the most fundamental one made in the laboratory; indeed the determination of most physical magnitudes depends ultimately upon the measurement of a distance. The simplest method of measuring a given distance is to make a direct comparison of it with the length of a standard scale.

APPARATUS: Rectangular block of wood and rule divided in millimeters (the latter may well be a piece cut from a meter stick and need not have the zero of the scale at the end); trip balance and weights.

DIRECTIONS: First read the Introduction through carefully paying particular attention to Arts. 1, 2, 3, 4, 5, 7, and 8. Measure the block in accordance with the following principles:

1. *Make several measurements* of each dimension and take the mean or average. In the present case a suitable number would be five for each dimension, made on different parts of the block. The average of these will be obviously of greater accuracy than any single measurement. In making these measurements it is not generally desirable, nor, in fact, always possible, to use the end of the rule as the zero from which to start the measurement. It is good practice to place the rule on the block so that one edge of the latter comes at some scale division and subtract this reading from that at the other edge.

2. *Always estimate to tenths of the smallest scale division.* In this case the metric scale divided into millimeters will be used. The readings then should be *to tenths of a millimeter.* Each dimension being expressed in centimeters, sample readings