A LABORATORY COURSE IN PHYSICS

MILLIKAN AND GALE

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FOR SECONDARY SCHOOLS

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GINN & COMPANY
BOSTON · NEW YORK · CHICAGO · LONDON

68.7

The Athenæum Press
GINN & COMPANY · PROPRIETORS · BOSTON · U.S.A.

INTRODUCTION

Although laboratory work is now generally recognized as an indispensable part of any adequate course in elementary physics, it is nevertheless a lamentable fact that there are still some schools in which it is not attempted at all, while there are others in which, despite the most expensive equipment, the laboratory fails, on the whole, either to interest or instruct.

Both of these conditions are probably attributable to one and the same cause. In our modern glorification of the laboratory method, particularly of exact, quantitative measurements, and in our haste to get away from the superficial, descriptive physics of thirty years ago, some of us have undoubtedly gone so far as to defeat our own aims. We have made the laboratory an impossibility in schools which are financially weak, because we have made its expense prohibitive; and we have made it a disappointment in other schools which are financially strong, because in our eagerness to show our students exactly *how much* we have neglected to show them *how* and *why*. In short, the gravest danger which threatens the efficiency of the high-school laboratory to-day is the danger which arises from the creeping over of the methods and the instruments of research and specialization from the university into the high school, where they have absolutely no place, — the danger that principles shall be lost sight of in the bewildering details of refined methods and refined instruments.

The primary aims of the authors in the development of this course have been: (1) to make it a continuous and inspiring laboratory study of physical phenomena, and as far as possible removed from a mere drill in physical manipulation; and (2) to reduce apparatus to its simplest possible terms and yet to present a thorough course in laboratory physics.

Such success as has been attained in the accomplishment of these ends has been due not merely to a large amount of labor and experimentation on the part of the authors, but also to suggestions which have come in from the score of schools in which this course has been given a thorough trial during the past three years, and especially to the expert assistance of the instrument maker, Mr. William Gaertner, who has so simplified the design of the apparatus herewith presented that a large part of it can now be made at home if desired. Even if it is all purchased, it need not cost more than fifty dollars for a complete set, and six such sets have been used most satisfactorily at the University of Chicago in conducting laboratory sections of twenty pupils. The authors recommend, however, that wherever conditions will permit, all of the pupils of a section be kept working upon the same experiment at the same time. This arrangement requires about half as many sets as there are pupils. With instructions as complete as those here given, the experience of a number of schools has shown that with fifteen sets one instructor can successfully conduct a class of as many as thirty pupils. Great care has been taken to incorporate only such experiments as experience has shown to be workable with large classes and with a minimum tax upon the teacher's time outside of laboratory hours.

Another feature of the course is that the experiments do not presuppose either any previous study of the subject involved, or any antecedent knowledge of physics. The laboratory work may be kept in advance of the class-room discussion throughout the entire course if desired. Indeed, in their own elementary work the authors prefer to let more than half of the experiments constitute the student's first introduction to the subject treated. Furthermore, students are neither instructed nor advised to study their experiments before entering the laboratory, for each experiment has been arranged to carry with it its own introduction.

As was to have been expected from the statement of the aims of the course, it has been made a thorough mixture of qualitative and quantitative work. Indeed, the endeavor to make an elementary laboratory course either wholly qualitative or wholly quantitative seems to the authors to result inevitably in artificial and irrational distinctions, and to be perhaps the most fruitful cause of the failure of laboratory work.

The most approved and most satisfactory division of time between the class room and the laboratory is three single periods per week in the former and two double periods in the latter. Abundant experience in schools quite variously situated has shown that the work herein outlined can be easily completed in two such eighty- or ninety-minute periods per week for thirty-six weeks, even when all the notebook work is done in class. The length of the experiments has not, however, been adjusted so as to fit, in all cases, one school period; first, because the lengths of school periods are so different in different schools, and second, because the authors have not wished to sacrifice the logical development of a subject to a consideration which is after all wholly artificial and mechanical. The division into experiments is made on the basis of subject-matter rather than of time. A considerable number of the experiments will be found to require two periods, while in a few instances two experiments can be performed in a single period. This arrangement has not been found to be at all objectionable where all of the pupils work simultaneously upon the same experiment, and even in courses which are conducted with but a few sets of apparatus the difficulties arising from this source have been found to be trifling.

In case individual teachers find it desirable to shorten or modify the course, the subdivisions of each experiment make omissions easy and simple. It has been an especial aim of the authors to make both this course and the class-room text which it is designed to accompany sufficiently flexible to give full play to the individuality of the teacher. Both books have therefore been made complete enough to allow of a considerable range of choice. The two books together constitute a one-year course in high-school physics. The laboratory portion has, however, been made completely independent of the other portion, and in a number of instances has been given as a short course by itself with very satisfactory results. It is the firm conviction of the authors, based upon a considerable experience, that in schools in which only a short course in physics can be offered, a course of this sort with laboratory work for its backbone is much more satisfactory than one based upon an abridgment of a class-room text.

With respect to the notebook the authors can express but little sympathy with any rigid, mechanical form of arrangement to which all experiments must be forced to conform, and they are convinced that in some schools the real study of physics has been sacrificed to the study of notebook form. Their directions to their own pupils are, "Fill out your notebook as you proceed with your work in the laboratory, and let it be merely a brief running record of what you do, of what results you obtain, and of what conclusions you draw." Blank books of coördinate paper are required, and left-hand pages are used for scratch-book purposes, i.e. they contain preliminary observations and computations, while right-hand pages contain the orderly outline of the work, including the title and subheads of each experiment as found in the manual, a very brief statement of what is done under each, an orderly statement of results (copied in some instances from the left-hand page), and conclusions. Outline drawings are encouraged whenever the idea can be expressed more quickly and clearly in a drawing than in words. In order to place especial insistence upon the conclusions, questions have been freely scattered through the text, the answers to which generally involve the conclusions which are to be drawn. In schools in which double laboratory periods cannot be obtained time may be gained, without sacrificing the real study of physics, by having the orderly part of the notebook work done at home. If still further time must be gained, the authors prefer to save it at the expense of the written work rather than at that of the experiments, oral answers and discussion in the laboratory replacing some of the written work called for.

For the benefit of those who use both this book and the authors' class-room text a suggested time schedule for a thirty-six weeks' school year is inserted in Appendix A. Whether this particular schedule is followed or not, it seems to the authors a matter of great importance that each teacher begin his year with some well-considered time schedule before him, and that he plan each lesson and make his omissions and additions with this schedule in mind. Otherwise it almost invariably happens that the subjects treated in the first half of the text receive a disproportionate amount of time.

In Appendix C will be found a complete list of the apparatus desirable for the course. The experiments do not, however, preclude the use of the more expensive forms of instruments which are already common in the equipment of high schools, although the authors believe the simpler apparatus to be, in general, the more instructive.

The form which has been given to the Boyle's Law experiment (page 26) was first called to the authors' attention by Mr. C. H. Perrine of the Wendell Phillips High School, Chicago, although a modification of the same method is found in the admirable laboratory manual by Nichols, Smith, and Turton. The experiment on the cooling of acetamide through its change of state is the authors' modification of a similar experiment on acetanilid suggested to them by Dr. C. E. Linebarger of the Lake View High School, Chicago. The experiment on the mechanical equivalent of heat (Experiment 20) is similar to one described in Edser's *Heat*. The remaining experiments are either so familiar as to be common property or else have been devised by the authors. The single balance, which serves all the purposes of the course, was designed especially for it by Mr. Gaertner, with a view to gaining the great advantages which the suspended-beam type of balance possesses over the trip scale, and at the same time doing away with the nuisance of small weights. The apparatus used in the study of electricity is nearly all new, and, though very inexpensive and apparently crude, has proved extremely satisfactory.[1]

Among the large number of teachers who have already used the course and who have assisted in perfecting it, the authors are under especial obligation to Dr. G. M. Hobbs, Dr. C. J. Lynde, and Mr. F. H. Wescott of the University High School, Mr. George Winchester, now of Washington State University, and Mr. Harry D. Abells of Morgan Park Academy.

R. A. M.
H. G. G.

[1] All of the apparatus for the course can be obtained either of William Gaertner & Co., 5347 Lake Avenue, Chicago, or of the Central Scientific Company, 18 Michigan Street, Chicago.

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LABORATORY PHYSICS

EXPERIMENT 1

EXPERIMENTAL DETERMINATION OF π

(*The ratio of the circumference of a circle to its diameter*)

(*a*) *Measurement of circumference.* Measure the circumference to an accurately turned disk in the following way. Scratch a short mark A (Fig. 1) on the face of the disk perpendicular to its edge. Stand the disk on edge on a meter stick so that the mark A is very accurately above some chosen division B, e.g. the 10-cm. mark of the meter stick.

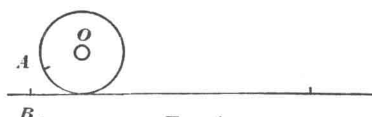

FIG. 1

Then, supporting the disk by causing the thumb and forefinger to meet through O, roll it very carefully along the meter stick until it has turned through one complete revolution. (Don't touch circumference in rolling.) The mark A will fall on some point of the scale. If it does not fall exactly on one of the millimeter divisions, in order to retain a decimal system throughout, record the fractional part of the last division in *tenths*, not in halves, thirds, or quarters.[1]

[1] Unfamiliarity with the metric system may make it seem more natural to estimate in halves, thirds, or quarters, but it will be easy to express the result in tenths if one reflects that .4 is a little less, and .6 a little more, than 1/2; .2 a little less and .3 a little more than 1/4; .1 a little less than .2, i.e. 1/5, etc.

Repeat the measurement and estimation four times, starting at a different point on the scale each time. Take a mean of these five readings as the most correct value of the circumference obtainable by this method.

Since the separate observations were uncertain in the tenths millimeter place, the mean will surely be uncertain in the hundredths millimeter place. To reserve places beyond this, then, would not only be useless but misleading, since it would indicate that the measurement was made to a higher degree of accuracy than it really was. The best usage in recording physical observations is to record one uncertain figure, but never more, except in recording the mean of a considerable number of observations, when one more figure may be retained, especially if the difference between the individual observations is slight. If this uncertain figure happens to be zero, it should be recorded like any other digit.

Fig. 2

(*b*) *Measurement of diameter.* Next measure the diameter of the ring with a meter stick held on edge as in Fig. 2. Record five observations taken along different diameters, and take the mean, estimating in each case to tenths of a millimeter.

(*c*) *Computation.* From these measurements compute π, the ratio of the circumference of a circle to its diameter. In the result save only one uncertain figure.

To find the first uncertain figure in the result, divide as in the illustration, underlining the uncertain figures throughout.

$$
\begin{array}{r|l|l}
8.43\underline{6} & 26.5\underline{2} & 3.1\underline{43} \\
 & 25\,30\underline{8} & \\
 & 1\,212\underline{0} & \\
 & 843\underline{6} & \\
 & 3684\underline{0} & \\
 & 3374\underline{4} & \\
 & 3096\underline{0} &
\end{array}
$$

Compare the result of your measurement with that given by mathematical theory, viz. 3.1416. Find first the amount of the error, and then compute what per cent the error is of the whole quantity, e.g. if the result of your measurement is 3.14<u>3</u>, then by taking the difference between this and 3.1416 we get

$$\begin{array}{l} 3.143 \\ \underline{3.1416} \\ \quad .0014 = \text{error} \end{array} \qquad \begin{array}{l} 1\% \text{ of } 3.1416 = .031416 \\ \therefore \text{ Per cent of error} = \dfrac{.0014}{.031} = .045 \end{array}$$

In the last division only two significant figures were used in the denominator, since it is never necessary to find the per cent of error to more than this degree of accuracy.

Record measurements and computations as below:

Trial	*Diameter*	*Circumference*	
1	8.43	26.50	
2	8.45	26.55	
3	8.44	26.52	$\frac{\text{Circumference}}{\text{Diameter}} = 3.143$
4	8.43	26.50	
5	8.43	26.52	Error = .0014
	Mean 8.436	26.518	Per cent of error = .045

State in the notebook, beneath the results tabulated as above, what per cent of error would have been introduced into the result if you had made an error of .1 mm. in measuring the diameter. (Find what per cent .1 mm. is of the whole diameter 8.436.)

State, therefore, whether your error is more or less than should have been expected from reasonably careful measurements. (Put your answers into the form of complete sentences.)

EXPERIMENT 2

DETERMINATION OF THE VOLUME OF A CYLINDER

I. By computation from linear measurement.

(*a*) *Measurements.* Measure with a metric rule the inside depth of the cylindrical vessel shown in Fig. 8, in three different places, estimating as before very carefully to tenths of a millimeter.

Measure the inside diameter D with a vernier caliper,[1] if this instrument is available; if not, use the method of the previous experiment, taking pains that the edge of the meter stick is held in every case exactly across a diameter.

(*b*) *Computation.* Compute the volume of the cylinder from the area of the base $\left(\frac{\pi D^2}{4}, \text{ or } \pi R^2, R \text{ being the radius}\right)$ and the height L. Underline all uncertain figures, and save only two uncertain figures in the result.

The following illustrates the method of computation:

$R = 2.5\underline{13}$ cm.	$R^2 = 6.3\underline{15}$	$\pi R^2 = 19.8\underline{4}$
$2.5\underline{13}$	$\pi = 3.14\underline{2}$	$L = 8.0\underline{1}$
$\underline{7}\ \underline{539}$	$\underline{12}\ \underline{630}$	$\underline{19}\ \underline{84}$
$\underline{25}\ \underline{13}$	$252\ \underline{50}$	$158\ 7\underline{2}$
$1\ 25\underline{6}\ \underline{5}$	$63\underline{1}\ \underline{5}$	$158.\underline{91}$ = volume
$5\ 02\underline{6}$	$18\ 9\underline{45}$	in cubic
$R^2 = 6.3\underline{15}$	$\pi R^2 = 19.8\underline{41}$	centimeters

[1] The vernier is a device for measuring fractional parts of a scale division. It consists of a movable scale AB arranged to slide along a fixed scale CD (Fig. 3). The object to be measured is placed between the jaws EF, which are so made that when they are in contact the zero of the sliding scale is opposite the zero of the fixed scale.

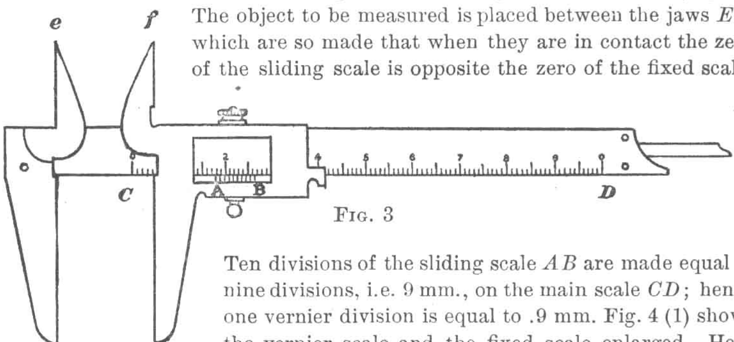

Fig. 3

Ten divisions of the sliding scale AB are made equal to nine divisions, i.e. 9 mm., on the main scale CD; hence one vernier division is equal to .9 mm. Fig. 4 (1) shows the vernier scale and the fixed scale enlarged. Here the zero of the vernier is exactly opposite the 5-mm. mark of the fixed scale, this being the relative position of the two scales when an object 5 mm. in diameter is placed between the jaws. Since one division on

Tabulate your results in some form similar to the following:

	First observation	*Second observation*	*Third observation*	*Mean*
Height of cylinder	= 8.26 cm.	8.25 cm.	8.25 cm.	8.253 cm.
Inner diameter of cylinder	= 6.04 cm.	6.03 cm.	6.04 cm.	6.037 cm.
	$\therefore R = 3.019$		$\therefore$ Volume = 236.2 cc.	

Write in your notebook answers to the following questions, using complete sentences as in Experiment 1.

If the diameter of a circle is measured as 10.1 cm. when it is actually 10 cm., by what per cent will the square of the diameter as measured differ from the square of the true diameter? (If in doubt, work it out.) Hence what per cent of error will be introduced into the computed value of the area of a circle, if there is an error of 0.3 per cent in the measurement of the diameter?

AB is equal to only .9 mm., while one division on *CD* is equal to a whole millimeter, it follows that the mark 1 of the sliding scale *AB* is .1 mm. behind the mark 6 of the fixed scale; 2 on *AB* is .2 mm. behind 7 on *CD*; 3 is .3 mm. behind 8; 7 is .7 mm. behind 12, etc. Therefore, if the sliding scale were moved up so as to bring its mark 1 opposite the mark 6 on the fixed scale, its zero mark would move up .1 mm. beyond 5. If the vernier had moved up until its 5 mark were opposite 10 on *CD*, the zero mark would have moved .5 mm. beyond 5, etc. In general, then, it is only necessary to observe which mark on the sliding scale

(1) (2)

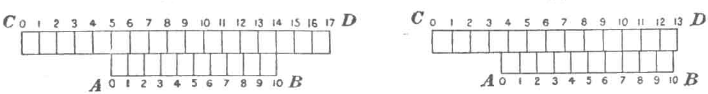

FIG. 4

AB is directly opposite a mark on *CD*, in order to know how many tenths of a millimeter the zero mark of *AB* has moved beyond the last division passed on *CD*. Thus the reading in Fig. 4 (2) is 3.7 mm. (.37 cm.), since the zero mark of the vernier has passed the 3-mm. mark on the fixed scale *CD*, and the 7 mark on the vernier is directly opposite some mark of *CD*.

In order that the *interior* as well as *exterior* dimensions of hollow objects may be readily determined, the jaws *ef* (Fig. 3) are added in many vernier calipers. These jaws are inserted just inside the walls and the reading taken as described.

If you misread the diameter of your cylinder by 0.1 mm., what per cent of error did you thus introduce into the diameter? into the computed area of the base of the cylinder? into the computed volume of the cylinder?

II. By weighing the cylinder first when empty and then when filled with water.

(*a*) *Weighing cylinder by method of substitution.* Place the empty cylinder with its ground-glass cover on the pan *B* (Fig. 5) of the balance, and add to the other pan any convenient objects, such as pieces of iron, shot, and bits of paper, until the pointer stands opposite the middle mark at *s*, the rider *R* being at zero.

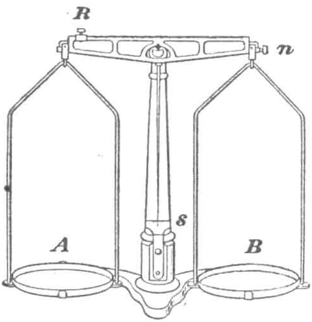

FIG. 5

Then replace the cylinder and cover by weights from the set in the following way. Find by trial the largest weight which is not too large, and place it on pan *B*. Add the equal weight, or, if there is no equal, the next smaller one, if it is not too heavy; add again the equal or next smaller weight, and so on, always working down from weights which are too large. This saves the delay and annoyance caused by adding a large number of small weights and at last finding that their sum is still too small.

When a balance has been obtained to within 10 g., slide the rider *R* along the graduated beam until the pointer stands opposite the middle mark at *s*. The weight of the body is then the sum of the weights on the pan plus the reading of the left edge of the index *R* on the graduated beam. Since each division of the scale on the beam represents one tenth of a gram, by estimating to fractional parts of a division we can obtain the weight by this method to hundredths of a gram.