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CHIROLD D. EPP

LABORATORY EXPERIMENTS IN COLLEGE PHYSICS

fifth edition

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FIFTH EDITION

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Preface to First Edition

This laboratory manual is designed for students who are taking their first course in physics, and the order of the subject matter of the experiments is approximately as found in most of the standard textbooks for first-year college physics. The experiments are independent of each other, however, and may be used in any order desired.

In practically all the experiments the apparatus is of simple design and of a type found in most physics laboratories. The author believes that the fundamental principles of physics can best be learned through the use of simple apparatus. If high precision is required in a first course in physics, much of the understanding of fundamental principles is sacrificed to acquiring skill in operating complex equipment. At the beginning of each experiment there are two lists of apparatus. One list includes the items the student will check out of the supply room; the other list includes the apparatus the laboratory instructor will place in the laboratory to be used as needed. These two lists include *every item* of equipment needed, thereby simplifying the procedure of determining all the necessary pieces of apparatus to operate the laboratory.

In addition to the list of apparatus, the instructions for each experiment include a statement of the purpose of the experiment, an introduction summarizing the physical principles involved, and directions for the experimental procedure. A description of the operation and use of the apparatus is included in some of the experiments where such an explanation seems necessary. It is assumed that in most cases the experimental work will accompany or follow the corresponding subject matter in the textbook, and consequently only a brief summary of the theory is given in the introduction.

The questions that follow each experiment are designed to aid the student in making more careful observations and to train him to analyze these observations and interpret the results. Many of them are questions the student cannot answer unless he has been a careful observer. The author believes that the answers to these questions give a very clear indication of the student's grasp of the experiment, and are a very important part of the report handed in to the instructor.

Forms on which the data and results may be recorded are included with most of the experiments on perforated sheets so they may be detached and handed in as part of the report. They are omitted in two or three experiments because the data is of such nature that it cannot be fitted to a tabulated form.

The experiments are designed for a three-hour laboratory period, if all the calculations are made and all questions answered during the laboratory period. If only a two-hour period is available and the instructor desires to have the computations completed within that time, the experiments are so arranged that certain parts of each can be omitted. The use of modern calculating devices will also shorten the time needed for completing the experiments.

C. H. BERNARD

Preface to Fifth Edition

The general nature of the makeup of this laboratory manual and other useful information about its philosophical approach to experimental work is outlined in the preceding Preface to the First Edition. The general format of the *Fifth Edition* is somewhat modified from that of previous editions, and its design and scope has been broadened to serve a greater spread of student preparation and relate more closely to the needs of teacher and student in today's physics laboratories.

In the preparation of this edition, nearly two-thirds of the retained experiments have undergone some revision. One experiment (in Optics) has been deleted, others revised, and three replaced (in the *Electricity and Magnetism* section). The replacements deal with measurements on Kirchhoff's circuit rules; charge and discharge transcients in capacitors; and the action of RLC combinations in alternating current circuits. New, or alternate, equipment has been added to some experiments. The revision process has involved every major section of the manual from the General Introduction to the Appendix. The sections on *Mechanics and Electricity* have received the most extensive revision, probably because they make up about sixty percent of the book. The remainder covers the other six sections. In addition, more than one-half of the data forms have been revised and expanded to provide more space for recording calculated and graphical results from observed data.

As in previous editions, a number of teachers have indicated that they are using the book for two levels of courses in general physics. In order to better serve this dual purpose, alternate procedures and methods of data analysis are now available in several of the experiments. These alternate procedures offer the option of placing greater emphasis on graphical analysis for instructors who prefer to. Also, in several places, the instructor is alerted to a method of combining two experiments into one when the material is related, thus permitting a faster pace in the lab program. With this flexibility, this laboratory manual provides sufficient experiments for a full two-semester program for each of the two levels of general physics.

The questions at the end of each experiment have been expanded in several instances. Also they are so graded that the instructor may select questions best fitting the preparation and background of the student. These questions are designed to accomplish the following goals:

1. To stimulate careful observation of physical phenomena.
2. To develop an inquisitive attitude toward what is observed.
3. To promote precise measurement practice and improve technique.
4. To serve as a guide in analyzing experimental data.
5. To add fulness to the written report relative to the significance of the findings.

If the student writes the answers in essay form, each as a separate paragraph, the answers supply a smooth analysis and summary of the experimental results. The instructor, to promote the best continuity and smoothness to reports, may suggest a particular sequence for the answers.

In replying to a questionnaire inviting comment, respondents furnished the suggestions for much of the revision in this *Edition*. Each idea submitted was carefully weighed and considered, but it was neither feasible nor practical to use every suggestion received. The indication of experiments presently being used in laboratories has served as a guide in determining which to delete and which to replace.

Our gratitude goes to Bernard O. Beck and Company, Central Scientific Company, Leeds & Northrup, and Sargent–Welch Scientific Company, for the continued permission to use their photographs of apparatus. We wish also to express here our appreciation to John Wiley & Sons and their physics editor, Mr. Robert A. McConnin, for the fine cooperation during the preparation and publication of this new edition and to Mr. Donald H. Deneck, former physics editor, for his assistance in formulating the revision.

We extend our many thanks to all who submitted suggestions for the revision, with a special recognition to Mr. J. P. Culwell, of Okaloosa–Walton Junior College, who sent an abundance of very useful ideas. Professors Raymond Sims and E. L. Holverson, of Midwestern State University, have been very helpful in testing some of the experiments in laboratory classes and in evaluating parts of the manuscript. We are also indebted to Mrs. Paula Shaw and Mrs. Maxie Bernard for their work in typing and assembling the manuscript.

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Introduction

I. General Laboratory Instructions

The student should read the entire Introduction very carefully since references to it will be made in many sections of this book.

1. *Laboratory Objectives.* The laboratory is the workshop of the student, the place where he gets a firsthand knowledge of physical principles and experimental methods through the handling of apparatus designed to demonstrate the meaning and application of these principles. Some of the more specific objectives are: (a) to acquire training in scientific methods of observation and recording of data; (b) to acquire techniques in the handling and adjustment of equipment; (c) to get an understanding of the limitations and strengths of experimentation; (d) to obtain experience in the use of graphical representation; and (e) to collect data, and to develop confidence in one's ability to compute reliable answers or to determine valid relationships. When one develops the skill of computing answers from experimental data which check with known values of the desired quantities, he acquires the confidence needed to perform an experiment and determine some quantity or relationship which was previously not known to anyone.

2. *Development of Character and Sense of Responsibility.* Prospective employers and placement offices frequently send questionnaires to physics instructors requesting information concerning the character, attitudes, honesty, and dependability of students. The instructor makes his evaluation of these traits from observations of the student's performance in class and in the laboratory. The laboratory is a place for serious thought and investigation, and the following suggestions should help you to develop the above-mentioned traits.

a. Be prompt in arriving at your work station and be well prepared concerning the principles of the experiment. If, for some good reason, you are late or absent, report the matter to the instructor.

b. Work quietly and attempt to make the most careful observations possible by adjusting the equipment so that it will give its best possible performance.

c. Be honest in making and recording observations. Record data as indicated by your equipment and not as you thought it was supposed to be, if they differ. *Copy no data, conclusions, or computations from any source.* If your results seem to be outside the limits predicted by the experimental uncertainties, recheck your measurements and computations. If this does not give the answer, make the best possible explanation for the discrepancy.

d. Have the entire procedure well in mind and perform the various steps in the order that will make the best use of your time. Cooperate with your partner so that each of you gets experience in manipulating the equipment. Then, each of you should compute your results independently to check on the accuracy of your work.

e. Always remain at your assigned station and do not disturb other people in the class concerning any part of the experiment. Do not disturb other equipment that may be in the room but is not a part of your present experiment.

f. Always abide by any precautions that your instructor may have given you regarding the proper handling of the equipment. Delicate equipment may be easily damaged.

3. *Preparation for the Actual Laboratory Work.* The efficiency of performance in the laboratory depends largely on the preparation made before the experimental work begins. This preparation may consist of a careful individual study of the principles involved and a general idea of the procedure to be followed, or, your instructor may give a lecture on the experiment. In the lecture period which may, or may not, immediately precede the laboratory work, the instructor will state the purpose of the experiment, discuss the underlying theory in the "Introduction" section, and outline the experimental approach for obtaining the necessary data. He may also suggest techniques that should be used to get the best performance from the apparatus. The details of how to perform the experiment will be found in the "Procedure" section.

4. *Checking Out Apparatus.* A list of apparatus is given with each experiment, and the items listed as special apparatus will usually be checked out of the storeroom by the student. Perhaps only one student will sign for the equipment issued, but all students working as a partnership will be held equally responsible for its care. Check each item of the equipment received, and make sure that you have all articles required and that all are in good condition. Also check apparatus already on the table and compare it with the items listed under general apparatus. Report any irregularities to the instructor or his assistant at once.*

5. *Materials which the Student Will Supply.* Equipment which is not considered as general laboratory apparatus will be needed at various times. These items consist of graph paper (20 lines to the inch), straight edge, protractor, slide rule, hand calculator, and watch with sweep second hand. You should always have your textbook available for reference.

6. *Performance of the Experiment.* Before beginning the experimental work always read the entire procedure to get a general idea of what is to be done. You should always arrange and adjust the apparatus to give the best performance possible and then make and record readings as precisely as the apparatus will permit. Always estimate one significant figure beyond the smallest graduation on the instrument being read.

Data *should never* be recorded on *scrap paper* and then transferred to your record form. If, after you have recorded a reading, you decide that it is in error and should be discarded, mark through it and record the corrected reading below it. Always record the proper unit beside the number or at the heading of a column when a whole column of readings use the same unit.

*Near the close of the laboratory period all items of equipment checked out should be neatly arranged in the checkout box and returned to the storeroom.

Do not hesitate to discuss any details of the experiment with the laboratory instructor during the laboratory period. You may want to question certain procedures or suggest improvements in the method. A good question may be more important than a good answer.

7. *Report of Experimental Work.* The form of the report required will be designated by the instructor in the course. In any case, the original data should be presented in neat form, such as that suggested at the end of each experiment in this manual. The data should be followed by sample calculations showing the method of obtaining the results. If the experiment requires several computations of the same type, only one of each type need be shown in the report.

When all calculations have been made and curves (if any) plotted, the student should study the results and draw some conclusions concerning what relations are indicated and what physical principles are demonstrated. Many of the questions at the end of each experiment are intended to stimulate thought and to guide the student in drawing conclusions concerning the results. These questions are to be answered in discussion style, and the answers so worded that the reader can ascertain the question from the answer. The sheet containing the questions may be removed from the manual if the instructor prefers that both questions and answers be a part of the report.

8. *Proficiency in the Laboratory.* This will be determined by the neatness of the report, accuracy, conduct in the laboratory, technique in operating equipment, ability to grasp the fundamental principles demonstrated by the experiment, answers to the questions at the end of the experiment, and answers given to any quiz questions that may be asked on the laboratory work.

II. Errors and Significant Figures*

A. ERRORS AND UNCERTAINTIES IN MEASUREMENT

Because of human and instrumental limitations no measurement is absolutely accurate or exact. A measurement or experimental result is of little value if nothing is known about its precision. If we are concerned about the reliability of a certain measurement, we must know something about the probable errors and uncertainties that were involved in obtaining it. There are many types of errors which enter into measured quantities, and there are several ways of classifying them. One way is to classify them as (1) errors in calibration of the instruments, (2) errors inherent in reading the scale, (3) errors inherent in the insensitivity of the indicator to changes, and (4) errors due to fluctuations in the environment which affect the experiment.

Errors in the Calibration of the Instruments. These errors may result from an instrument being used under conditions different from those for which the calibration was made. If a measuring tape is calibrated to be used at 20°C, indicated measurements made at 30°C will not be the correct values. Some very delicate instruments must have the

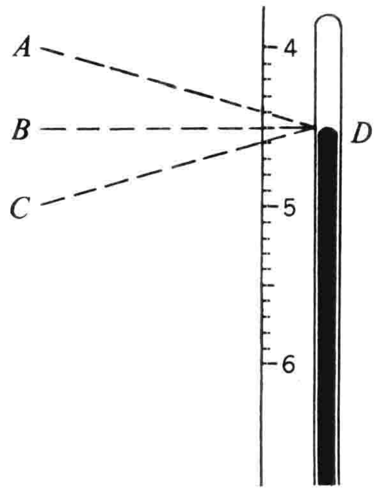
*For students doing experimental work in physics for the first time, Sections II and III of the Introduction can provide a worthwhile introductory laboratory (or class) exercise. A discussion by the instructor, coupled with student participation, will result in more careful and meaningful observations and better reports on all experiments assigned in the course.

calibration checked at periodic intervals. Instruments may also be worn by use to such an extent that precise settings cannot be made. One must also choose an instrument which is calibrated to give the precision required in the measurement. For example, an ordinary meter stick would not be appropriate for measuring the diameter of a small wire, which may be no larger than the smallest division on the stick.

Errors Inherent in Reading the Scale. A student's personal bias is often responsible for inaccurate results. When a series of trails are to be made for a certain measurement, students very often assume the first trial to be about correct and attempt to make all the others agree with it, thus giving more significance to the first reading than to any of the succeeding ones. Other personal errors are introduced because of insufficient care being used in adjusting instruments, inaccurate estimations of fractional divisions, and parallax.

The apparent distance between two objects will depend on the position of the eye. Two objects may appear to be in line when viewed with one eye but out of line when viewed with the other eye or when the head is moved to one side. This apparent change in position due to sidewise motion of the eye is called *parallax*.

If one is attempting to read the position of the mercury level in a tube near a scale (see Figure A) the line of sight must always be perpendicular to the scale. If one should sight along the line *AD*, he would read 4.4; if along line *CD*, he would read 4.6; the correct reading is 4.5, as read along the line *BD*.



A ERRORS IN SCALE READINGS DUE TO PARALLAX

The chance of error due to parallax between scale divisions and the object being measured may be reduced to a minimum by placing the measuring scale as near as possible to the object being measured. A meter stick should always be placed edgewise against the object being measured to reduce such errors.

Other problems associated with reading instruments might come under the heading of *random fluctuations*. As one attempts to read a voltmeter connected across some circuit element in the AC power line, the needle may fluctuate back and forth while one attempts to get a reading. The same situation exists in attempting to read the scale on a count rate meter connected to a Geiger tube. Methods of handling statistical fluctuations will be discussed in connection with the appropriate experiment in this book.

Errors Inherent in the Insensitivity of the Indicator to Changes. In some experimental setups, one indicating portion of the equipment may not show sufficient response to changes in other indicating parts. When a certain amount of weight is added in one place, friction in the connecting links may prevent a scale indicator from showing the proper response. It may be that some instrument is slow in responding to a change in temperature, and readings must not be made too quickly. The usual laboratory thermometer, calibrated in 1-degree divisions, could not be expected to show sufficient response to a temperature change of 0.01 degree.

Errors Due to Fluctuations in the Environment. If one is attempting to read an instrument out in the open where the adjustment is affected by gusts of wind, an accurate reading would be difficult to obtain. These types of errors, due to changes in the environmental conditions, can only be reduced through proper control of such conditions as temperature, humidity, noise background, vibration, stray electric fields, wind, and so forth. Sometimes these are beyond the control of the experimenter.

Percentage Error. The error in a measurement is the amount by which the student's experimental value differs from the accepted value listed in some official record, such as a handbook. It should be clearly understood that the amount of the error is not a true index of the precision of the measurement. For example, suppose one measures the distance between two streets to be 390 m, while a professional surveyor's record shows the distance as 400 m. In another case, a person estimates the width of a table as 1.8 m when it should be very near 2.0 m. The absolute error in the first case is 10 m, and in the latter case, 0.2 m. Which one would you say did the best job in his measurement? The one who measured the table made an error of 0.1 m in each meter measured. On this basis, he would have made an error of 40 m in the street measurement. The fractional error, which is the ratio of the absolute error to the accepted value, is the quantity which shows the precision of the measurement. In the above cases we have the following:

$$\text{First case, fractional error} = \frac{10m}{400\ m} = 0.025 = 2\tfrac{1}{2} \text{ parts in 100, or } 2.5\%$$

$$\text{Second case, fractional error} = \frac{0.2m}{2.0m} = 0.1 = 10 \text{ parts in 100, or } 10\%$$

$$\text{In general, percent error} = \frac{\text{absolute error}}{\text{accepted value}} \times 100$$

Percentage Difference. There are cases in which we want to compare the results of two equally trustworthy measurements, that is, to find the percentage difference between the two. For example, suppose two measurements of a length give 4.0 cm and 4.2 cm, respectively, the exact value not being known. The percentage difference is found by comparing the deviation (or difference) with the average of the two. Hence, we have

$$\text{Percentage difference} = \frac{4.2-4.0}{4.1} \times 100 = 0.049 \times 100 = 4.9 \text{ percent}$$

Estimated Uncertainties. The reliability of a given measurement is increased by obtaining the average of a number of *independent* readings. This average is likely to be a more reliable value for the measurement than one single reading. These fluctuations (or deviations) in the individual readings indicate that uncertainties do exist in experimental measurements. The average deviation may be obtained by finding the absolute value of the difference between the mean and the individual values, and then averaging these deviations. If M is the mean value and d is the average of the deviations from the mean, then the measured value of the quantity Q should be recorded as

$$Q = M \pm d$$

If only one reading is made, one may estimate the uncertainty by examining the scale being read and deciding by what fraction of scale division a reading could be in error. This may vary from 0.1 to 0.5 of the smallest scale division.

The percentage uncertainty, in terms of the above symbols is expressed by the relation

$$\text{Percent uncertainty} = \frac{d}{M} \times 100$$

B. SIGNIFICANT FIGURES

The digits required to express a number to the same accuracy as the measurement it represents are known as *significant figures*. If the length of a cylinder is measured as 20.64 cm, this quantity is said to be measured to four significant figures. If written as 0.0002064 kilometers, we still have only four significant figures. The zeros preceding the 2 are used only to indicate the position of the decimal point. The zero between the 2 and 6 is a significant figure, but the other zeros are not. If the above measurement is made with a meter stick, the last digit recorded is an estimated figure representing a fractional part of a millimeter division. *All recorded data should include the last estimated figure in the result, even though it may be zero.* If this measurement had appeared to be exactly 20 cm, it should have been recorded as 20.00 cm, since lengths can be estimated by means of this instrument to about 0.01 cm. When the measurement is written as 20 cm it indicates that the value is known to be somewhere between 19.5 cm and 20.5 cm, whereas the value is actually known to be between 19.995 cm and 20.005 cm.

Referring again to the 20.64 cm measurement, the possible error in this measurement is ± 0.005 cm and was recorded as being nearer to 20.64 than to 20.63 or 20.65. Hence, the uncertainty is less than one part in two thousand.

Now suppose the diameter of the cylinder is measured with the same instrument and recorded as 2.25 cm. This number has only three significant figures and, hence, is known to only one part in a little more than two hundred. From this we see that the number of decimal places does not indicate the precision of the measurement.

Now suppose we wish to find the volume of this cylinder as given by the relation $V = \pi r^2 h$. The radius r = 1.125 cm, four significant figures being retained because the original measured number has been reduced by the process of dividing by 2, thus giving rise to a larger percentage error from deviations in the third significant figure. The precision of the original measurement will determine when it is best to include an additional figure in such cases.

$$\begin{array}{r}
1.1\underline{25} \\
1.1\underline{25} \\
\hline
\underline{5625} \\
\underline{2250} \\
11\underline{25} \\
11\underline{25} \\
\hline
1.2\underline{65625}
\end{array}
\qquad\qquad
\begin{array}{r}
20.6\underline{4} \\
1.2\underline{7} \\
\hline
1\underline{4448} \\
4\underline{128} \\
206\underline{4} \\
\hline
26.\underline{2128}
\end{array}$$

An analysis of the multiplication processes above will be helpful in understanding the proper use of the slide rule and electronic calculator in computing experimental results. If we underline the doubtful figures in the number representing r and find r^2, the multiplication is as shown above.

The result is shown to be 1.265625. But if the doubtful figures are carried through the process of multiplication and only one of them kept in the final result, the value of r^2 is recorded as $1.2\underline{7}$. In dropping nonsignificant figures, the last figure retained should remain unchanged if the first figure dropped is less than 5, and should be increased by one if the first figure dropped is 5 or greater. This is the practice used in most experimental work. Thus, the first 6 in the above product is increased to 7.

If the first 6 in the result is doubtful, the other four figures in the result are worthless and should be discarded. In like manner, the product r^2h has a value of $26.\underline{2}$ when we include only one doubtful figure, and round off as indicated in the above rule. It should be noted that this final product contains no more significant figures than does the factor having the fewest significant figures, namely, 1.27, which has three.

The next step is to multiply by π, the value of which that you have most probably been using is 3.1416. This multiplication is being left as an exercise for the student under the supervision of the instructor and supplemented by his discussion.

First multiply the result of r^2h as given above by 3.1416, showing all the steps in the multiplication and indicating the doubtful figures, and record the final result to retain only one doubtful figure. Now multiply the value of r^2h by 3.14, and record the final result as containing one doubtful figure. How do the two results compare? What rule would you suggest concerning the number of digits to use for π in multiplication processes such as this? If the diameter of a certain circle is $9.8\underline{1}$ cm, with only one doubtful figure, what should be used as the value of π in obtaining the circumference of the circle? Check the validity of your answer by mutliplying $9.8\underline{1}$ by 3.14, then by 3.142, and finally by 3.1416. If you keep only one doubtful figure in the final result, how many significant figures of π are required, and how many significant figures are in your answer? Note that 9.81 is almost as large as 10.00, a number having four significant figures. Hence, one must carry enough digits in π to avoid introducing more uncertainty into the answer.

Now take the diameter of the cylinder as $3.2\underline{8}$ cm instead of $2.2\underline{5}$ cm and calculate the volume by following the doubtful figures through the multiplication process. If one doubtful figure is retained in the result, how many significant figures appear in your answer? Is this number any different from what you expected?

Significant Figures in Division. Your result from the first calculation of the volume should be $82.\underline{3}$ cm^3. Now suppose the cylinder weighed $784.\underline{7}$ gm, and we wished to find the weight per unit volume. We should find the quotient of $784.\underline{7} \div 82.\underline{3}$. By adding sufficient zeros to carry out the division in the usual manner, we obtain 9.534629 gm/cm^3 as the weight per unit volume. If the effect of the doubtful figures in both numbers is followed through, it should be noted that the number $9.5\underline{3}$ has as many significant figures as we are justified in keeping.

Significant figures in Addition. Suppose we desire to find the sum of the numbers in the first column at the right. Nothing is known about the 710 to the right of the decimal point. Hence, addition of digits to the right of the decimal point is meaningless. The numbers should be recorded as shown in the second column.

$81.57\underline{2}$	82
$71\underline{0}.$	710
$0.0\underline{3}$	
24.3	24
	816

General Rules for Computations with Experimental Data

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

II. *In multiplication and division,* carry the result to the same number of significant figures that there are in that quantity entering into calculation which has the least number of significant figures. If the first digit of this quantity is 7 or more, then for safety purposes, it should be considered as having one additional significant value.

III. *In dropping the figures* which are not significant, the last figure retained should be increased by 1 if the first figure dropped is 5 or more.

IV. *In using significant figures and calculating devices,* remember that most measurements in the general physics laboratory will have about three, and sometimes four, significant figures. Hence, a 10-inch slide rule will give the desired number of significant figures required for all calculations. If an electronic calculator is used to add the numbers in the above example, the column on the left will give a result of 815.902. However, when you examine the doubtful figures in the sum, you will note that the correct result to record is still 816. Hence, even though the calculator may register some 6 to 10 figures, the above three rules are still used in rounding off the recorded result.

The accuracy of calculated results from experimentally measured quantities is determined by the precision of the measuring instrument and cannot be improved by the calculating device. However, the use of the slide rule and electronic calculator is encouraged to save time.

III. Graphical Representation of Experimental Data

From an examination of the tabulated values of a number of measurements of related quantities, it is often difficult to grasp the relationship existing between the numbers. A method widely used to discover such relationships is the graphical method, which gives a pictorial view of the results and makes it possible to interpret the data by a quick glance.

Independent and Dependent Variables. In any experimental study of cause and effect the aim is to vary just one condition at a time (the cause) and to observe the corresponding values of another quantity (the effect) which is suspected of being related to the first. This existing relationship is most easily interpreted from the graph if the first of these quantities, the independent variable, is plotted on the abscissa scale (X-axis) and the dependent variable, is plotted on the ordinate scale (Y-axis). Very often the values to be plotted are all positive and only the first quadrant of a rectangular coordinate system will be needed. In such cases, the origin should be shifted to the lower left-hand corner of the sheet of cross section paper. When possible, draw the axes inside the margins of the graph paper along the first or second large square. This gives more space to write in the scale and also furnishes guide lines for lettering the names of the variables being plotted (Figure B). Graph paper with 20 squares to the inch is recommended for the curves to be plotted in this course.