G. F. C. Searle was in charge of practical physics teaching in the Cavendish Laboratory for some 50 years from 1890. Students under J. J. Thomson, Lord Rutherford and W. L. Bragg all experienced his firm views and discipline and in turn they took this experience with them when they dispersed across the world. Searle was particularly interested in 'Properties of Matter' (his book on that subject written jointly with F. H. Newman was a compulsory purchase for advanced physics students for decades) and he devised some good pieces of equipment for such measurements. He wrote other books too and in an appendix to his first production 'Laboratory Elasticity' published in 1908 by Cambridge University Press he gave his ethos on what to do and what not to do in the physics laboratory. Most of his dos and don'ts are still valid today and have been repeated by demonstrators the world over. They set the use of our historic laboratory instruments in context.

HINTS ON PRACTICAL WORK IN PHYSICS.

1. FAILURES. A demonstrator in practical physics spends a large part of his time in correcting students' mistakes. He has to discover, for instance, why it is that a student obtains 537·86402 [no units mentioned] for Young's modulus by an experiment on a brass wire instead of 9·86 x 10^{11} dynes per square centimetre. It is then found, perhaps, that the student has confused the radius of the wire with its diameter, that, having got hold of a screw-gauge in which one turn is equivalent to 1/50 inch, he has treated one turn as equivalent to 2 millimetre either because it looked about 2 millimetre when tested with a millimetre scale or because he did not care to ask those who knew, that he has measured the extension in millimetres and has then treated the millimetres as if they were centimetres and that he has used 32 for "gravity" instead of 981. When the crumpled sheet of paper has been unearthed from the rubbish box, the arithmetic on it is found to be faulty. The student has omitted (perhaps through caution) all reference to the units in which the result is expressed. In some cases the student adds the letters C.G.S. in much the same way as grocers add "ESQ." to customers' names. If his courage allows him to name the units, he often uses the wrong names; the chances are that he puts down "dynes."

The student may have learned something of the physical principles involved in the experiment and may have gained some practice in manipulation, but the result of his work, viz. that Young's modulus for brass is 537·86402, is worthless, and is entirely useless to any human being.

The following hints may perhaps assist the student to avoid errors in his work and may help him to discover where they have occurred when, in spite of all his care, his result is obviously wrong.

2. OBSERVATIONS. After the necessary adjustments have been made, the observer reads off a number from the graduations of the instrument or in other ways. The result of the experiment cannot possibly be correct if this number be not correctly read and correctly recorded. After the reading has been entered, the student should, when possible, look at the instrument again in order to detect any discrepancy between the *written entry* and the instrumental reading. What he *actually wrote is* not always what he *intended* to write.

The work of observing is liable to a great variety of errors. Some of the most frequent are the following:−

Wrong values are assigned to the divisions of a scale. Thus the student sees a 10 and counts on 5 more divisions, and enters the reading as 10.5 instead of 15. Or, when the main divisions are subdivided into 5 sub-divisions, one of the latter is taken as a tenth instead of a fifth of a main division.

The numbered divisions are read from left to right, but the tenths are read from right to left. Thus 25.4 is wrongly read as 25.6, the 6 tenths in the latter number being reckoned from the "26."

The student does not understand the graduation of the instrument, either because he has not given sufficient attention to the matter or because the unit of measurement is not marked on the instrument; in the latter case he cannot be expected to know the unit of measurement and he should ascertain it from those who have put the instrument into his hands, be they instrument makers, teachers, or examiners.

In most cases the determination of a physical quantity involves two observations. Thus, when the diameter of a wire is measured by a screw-gauge, the reading of the gauge when the jaws are in contact is required as well as the reading when the gauge is adjusted to the wire. But students frequently omit to take the zero reading. They should remember that "every length has two ends." The attempt to measure a length by a *single* reading sometimes leads to totally erroneous results, as when a distance of 30 cm. is put down as 70 cm. because the " wrong end " of the scale is used and so the distance to be measured lies between the "100" and the "70" on the scale, and not between the "0" and the "30." If, in addition to the reading "70," the reading "100" had been taken and *recorded,* the error would not have occurred. Similar remarks apply to the measurement of many other quantities, *e.g.* masses, angles, and resistances.

In finding the periodic time of a vibrating system, a student sometimes calls "one" when he starts the stop-watch; he stops the watch as he calls "fifty" and though he imagines that he has found the time of 50 vibrations, he has really found the time of only 49. He should call "nought" when he starts the watch.

When the periodic time exceeds about two seconds, the mind has time to ramble off to other interests between one count and the next, and therefore a special effort must be made to concentrate the attention on the work in hand. It is of assistance to count out loud. On account of the difficulty of counting correctly, the student should make at least two independent observations of any periodic time.

A steady hand, a keen eye, and a good general command of the body are essential in accurate physical determinations; mere intellectual power avails nothing by itself. Any rule of life which deviates from temperance in all things (including work) may be expected to render the hand less steady and the eye less keen, and so to lead to inferior work. University students whose fingers are deeply stained with tobacco do not, as a rule, become skilful observers, though they may show considerable ability in other ways.

3. THE RECORDING OF OBSERVATIONS. As soon as an observation has been made, enter the result in a note book, not on a scrap of paper. Do not wait to see the result

of a second adjustment before recording the result of the first one. Take the figures *as they come* without any attempt to force them into agreement with any preconceived value.

Enter *observations* and not merely *deductions.* Thus, if two readings of a vernier be 15.85 cm. and 17.32 cm., these are observations. The distance l.47 cm., through which the vernier has been moved, is a deduction from the two observations. If the student, without entering the numbers 15.85 and 17.32, does the arithmetic in his head and puts down 1.57 through error, he has no chance of detecting the mistake afterwards. If he had entered 15.85 and 17.32, he might have found the mistake in revising his calculation. The neglect of the simple rule of always *entering* observations before making any deductions from them is a very frequent source of error. No one, whatever his private opinion as to his own powers, is likely to do reliable work if he neglects this rule.

Enter the observations in an orderly manner without crowding, and do not write in three or four different directions on the paper.

Write all the numbers very plainly. The letters in a badly written word can often be guessed, but the neighbouring figures do not help the reader to decide whether the mark on the paper is meant to be a 5 or an 8. The position of the decimal point is the most important feature of any collection of figures; be careful, therefore, to mark the decimal point firmly and clearly.

Be careful to state clearly what it is that you have measured, and also the units in which the measurement is expressed.

If you have reason to reject any of your observations, cancel the entries by bold lines drawn through them, so that there may be no mistake as to what is rejected and what is retained. Neatness is here of secondary importance.

A beginner naturally believes that he is capable of making a correct copy of the results of a series of observations; he will learn by experience that, in spite of his most strenuous efforts, mistakes will occur. It is therefore essential that the student should cultivate the habit of making the original record of the observations good and clear, and that he should preserve it for reference. If any practical use is to be made of the results of an experiment, it is obviously important that the chances of error should be as small as possible. The power of entering observations in a clear manner will be of value in a practical examination, for the student will then be able to send in his original record and will not feel compelled to waste time by copying out his " rough " notes.

4. ARITHMETICAL REDUCTION of OBSERVATIONS. From the observations the result is deduced by arithmetical work. Without this work the result cannot be obtained, and the accuracy of the result depends upon that of the arithmetical work. This work should therefore be carried out with quite as much care as that given to the taking and recording of the observations. The arithmetic should be done in the book containing the observations, and the work should be arranged in an orderly manner so that it will bear inspection. It is wise to verify each step before proceeding to the next. Many students have the bad habit of doing the arithmetic on scraps of paper which they immediately destroy, as if they were ashamed of the work; yet no one expects them to obtain the results without doing the arithmetic.

For most purposes four-figure mathematical tables may be used; Bottomley's tables are convenient. The student should make himself acquainted with the contents of the book of tables so that he may know where to look for (say) the reciprocal of a number; and he will then not waste time in working it out by the aid of logarithms.

The slide rule is so convenient in those cases where moderate accuracy suffices, that the student should endeavour to become proficient in its use. But it must be recognised that its accuracy is limited.

Care should be taken to carry the arithmetic to a *sufficient* number of significant figures. The final result depends, of course, upon the data used in the calculations, but the arithmetic should be carried so far that no error is introduced into the result greater than (say) one tenth of that arising from the errors of observation. An example will make this clear. The value of the product 1.6736 x 2·7628 is 4.62382208, or to 5 significant figures 4.6238. But if we perform the multiplications, we find that

$1.7 \times 2.8 = 4.8$ to 2 figures
$1.67 \times 2{\cdot}76 = 4.61$ to 3 figures
$1.674 \times 2.763 = 4.625$ to 4 figures.

Hence the rough 2 figure arithmetic has introduced an error of about one in 25. With 3 figure arithmetic the error is reduced to about one in 330, and with 4 figures the error is only about one in 4000.

On the other hand, it is useless to retain many significant figures in the arithmetic when the data are only correct to a few significant figures.

When the number of significant figures is to be reduced by rejecting the last digit *L,* the last but one is left unchanged when L is less than 5, and is increased by unity when *L* is greater than 5. When *L is equal* to 5, the last digit but one is left unchanged if it is even, but is increased by unity if it is odd. Thus 3.485 is shortened to 3.48, but 6.235 is shortened to 6.24; in each case the number adopted after the rejection of the " 5 " has its last digit *even.*

When the numbers are very great or very small, it is best to write them thus: 4.19×10^{7} or 5.89×10^{-5}, keeping *one* significant figure only on the left of the decimal point. There is less chance of error in copying 5.89×10^{-5} than in copying 0.0000589. This plan has the advantage that, when the logarithms of the numbers are to be found, there is no need to count the number of figures between the decimal point and the first significant figure. The power to which the 10 is raised is equal to the characteristic of the logarithm. Thus

$$\log(4.19\times10^{7}) = 7.6222, \quad \log(5{\cdot}89\times10^{-5}) = \bar{5}.7701.$$

The value of π is 3.14159265.... It is quicker to use log 3.41... than to use log 22 and log 7, as is necessary when the rough value 22/7 is employed. Gross errors in arithmetic can often be detected by the exercise of a little common sense. Thus a moment's thought shows that the cross-section of a wire one-tenth of a centimetre in diameter is not 2.345 square centimetres. The student should make a practice of looking at the result of each step to see if it is reasonable or absurd.

5. DIAGRAMS. When series of observations are plotted on squared paper, the student should express very clearly upon the diagram the two physical quantities which are represented along the horizontal and vertical axes. When this information is not given, the diagram is generally worthless. The points plotted on the diagram should be clearly marked by small circles drawn round them or in other ways.

In every case when a series of observations is made, one quantity X is varied and the consequent variations of a second quantity Y are observed. The quantity X should be varied over the whole of the available range and the separate values of X −say X_1, X_2 ... should be fairly distributed over that range. Many students are inclined to take X_1, X_2 ... so close together that they are unable, for lack of time, to cover more than a small part of the whole range. In such cases, it often happens that the errors of observation cause the points plotted on the X-Y diagram to be suggestive rather of a constellation than of any regular curve. If the intervals X_2-X_1, X_3-X_2, etc., had been large, the errors of observation would not have completely obscured the law which the experiment was designed to investigate.

6. NOTE BOOKS. The student should, if possible, keep a note book in which to write fuller accounts of the experiments than is possible in the laboratory. He will thus find out how much he has understood of what he has done in the laboratory, and will also gain practice in describing experimental work in his own words. The note book should have large pages, and ample space should be left for future notes and additions. But however great the labour spent upon this book, it can never take the place of the laboratory note book in which the original records are written.

The student should write his name and address in his note books as a safeguard against their loss.

7. GENERAL REMARKS. The student should not leave an experiment while there is anything connected with it which he does not understand. Every experiment involves many principles, and thus a single experiment thoroughly grasped in all its details puts the student in possession of much knowledge which will help him in future experiments. Hence, one experiment well understood is of far more educational value than a dozen in which the student has gained only hazy notions.

There is no such thing as the ANSWER to any experimental investigation, for no two persons would obtain *precisely* the same result, however carefully they worked. The student should have confidence in his results until he discovers an error in his work. But he should not pretend to do impossibilities. It is easy to make some measurement, such as weighing, with a great show of precision, but the precision is only apparent and not real unless the proper precautions have been taken and the proper corrections have been applied.

As the degree of exactness to be reached in any measurement is increased, the practical difficulties increase enormously. Thus with a household balance and household weights a cook could weigh a mass of aluminium of about 100 grammes to one gramme. A junior student with a cheap laboratory balance and common weights could weigh it to 1/10 gramme. To be certain of the mass to 1/100 gramme, it would be necessary to use double weighing and to allow for the buoyancy of the air. To reach an accuracy of 1/1000 gramme, it would be necessary to have a table of corrections for the weights employed, while to come within 1/100,000 gramme would require an accurate knowledge of the pressure, the temperature and the hygrometric state of the air, and would require the refined appliances of a national physical laboratory and the skill of an expert.

The student should have an eye to proportion. It is useless to make some observations (e.g. of mass) to one part in ten thousand when other observations in the same experiment can only be made to one part in a hundred (e.g. rise of temperature).

The formula which expresses the result in terms of the quantities to be observed should be carefully examined to see which quantities are of primary and which are of secondary importance. Thus the formula

$$K = M(\frac{1}{3}L^2 + \frac{1}{4}A^2)$$

for the moment of inertia of a cylindrical rod of mass M of length $2L$ and of radius A, shows that, when L is great compared with A, the quantities M and L are of primary importance, while A is of only secondary importance. It is useless to spend time in measuring $2A$ accurately by means of a screw-gauge when $2L$ is only measured to the nearest millimetre, for it is, at the outside, only the first two significant figures in $\frac{1}{4}A^2$ which are of any consequence compared with $\frac{1}{3}L^2$.

The end