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Turning a Diffident Student into a Competent Experimentalist – a Blueprint*

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Students from developing countries have often not had an opportunity to undertake experimental work because of the lack of laboratories where they have been studying. There can be several reasons for this: usually economic, but sometimes cultural. Whatever the reason, if students come to laboratory work later in their careers, rather than at the normal middle school stage, there are some hurdles that need to be overcome. There is an issue of confidence, there are background reporting skills to be learned, there is the *feel* for the limitations of an experiment, there is a need to appreciate how to logically design an experiment, an appreciation has to be gained in how to handle delicate equipment and there needs to be practice in interpreting results. A variety of methods have to be used to tackle these problems. In this article, the author describes some of the techniques that have been attempted to overcome these hurdles and comments on their effectiveness; these techniques range across tutorials, case-studies, practical demonstrations, specially designed short laboratory exercises and even formal instruction. The question of instilling safety awareness in all experimental work and demonstrations of hazardous situations is considered. The subtle qualitative difference in effect that open-ended experimental work has on a student compared with closed work is discussed Finally, there is a discussion of how the whole laboratory experience can be improved for all students.

INTRODUCTION

Established engineers and scientists who have been exposed to the rigours of experimental work from their early teens tend to underestimate how many background practical skills they have unconsciously imbibed over their working careers. They forget how little they knew when they first started, how woefully lacking they were in experimental procedures and generally how incompetent they were in the laboratory. However, by some means or other, their skills improved and they learned to cope [1]. If they were lucky, they were guided in their early years, step-by-step, into an appreciation of the intricacies of experimental work, an awareness of the limitations and the fragility of instrumentation.

When children first embark on a new learning experience, it is assumed that their background experience is limited and allowance are made accordingly [1][2]. They are given simple tasks to perform initially and each step is carefully explained to them. So they grow in confidence and competences, and progress to more and more complex and sophisticated procedures. However, the same allowances are not generally made for older students when they first come to work in a laboratory. It is assumed that they already have background knowledge and they are expected to dive into complex and sophisticated laboratory work almost immediately [3][4]. However, why should such assumptions be made? It is quite likely – it is more than likely – that many students come from backgrounds in which there has been no opportunity to undertake experimental work.

These older students must be given an opportunity, through carefully graded and structured laboratory

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work, to gain the practical skills which they are lacking. If such an opportunity is not offered to them, then they will rapidly become disheartened and not only will they not be able to cope with the demands of laboratory work, but they will not gain an appreciation of the limits and possibilities of engineering in general. This will carry over to the more formal theoretical side of their instruction. They will lose in interest in the subject. They will drift into other, less practically demanding, areas and be lost to engineering.

SOME SKILLS TO BE LEARNED

Dexterity

The first thing that students need to learn about the handling of equipment is that it is delicate. In fact, the first laboratory exercises may appear to be trivial – but they are not! How to handle glassware without breaking it, making allowance for the fact that heated objects tend to expand, that overheated objects tend to degrade, realising that precision instruments may contain machined parts that do not consist of infinitely hard material and so should not be tightened excessively, that other materials may be extremely hard, but they can also be brittle and fragile. An appreciation of all these limitations, and many others, need to become so inured that proper treatment of equipment becomes second nature.

Safety Awareness

Nowadays, people are aware of health and safety rules regarding their own conduct, but a safety assessment of an experiment rig is not an intuitive procedure and quite a number of features need to be spelled out. Firstly, an astonishing number of materials are flammable if they have a large enough surface area. Cereal flours and fine sawdust are actually explosively inflammable if tossed into the air, by a simple breeze for instance, in the presence of a lighted match or even a smouldering cigarette. Wire wool and sintered bronze will burn freely in the air if heated by only a few hundred degrees. So, for instance, if wire wool falls across the terminals of a flashlight battery, the result is an instant conflagration!

There is a tendency to think that if a low-voltage dc supply is being used to drive an electronic circuit, then there is no danger of sparking occurring. But if that electronic circuit contains a resonance section, then it is quite possible for a potential difference of a few hundreds of volts to be reached and then there is a potential danger for sparking.

Students are often taught of the importance of earthing electrical equipment, but if two connected electronic devices are separately earthed and one of them contains an active power source, then a virtual current loop can be created between them and quite large currents can flow. Again, this is a potential source of fire.

Prudent behaviour when heating liquids is a topic that many people claim is *common sense*, but it is astonishing how uncommon this often is. Uneven heating leading to uneven boiling or cavitation can lead to spurting of a liquid and so the following should be inculcated:

- Safety goggles should be worn (and maybe other protective clothing);
- If a test-tube is being heated then its mouth should not be pointing at the next student in line.

Some liquids are corrosive, while others give off toxic fumes (even at low level), and so pipetting should not be done by mouth. A rubber pipetting syphon should be used. The heat of a solution often leads to astonishing temperature rises that can cause scalding and also spurting. All of these effects need to be raised into students' consciousness and need to be deliberately raised into their conscious awareness zone.

Load-bearing limitations and the safe handling of heavy materials is another area where simple precautions, more uncommon *common sense*, need to be inculcated. This links with the safe handling of materials in general: be they heavy, benign or corrosive, toxic, radioactive – or whatever. There are simple rules of behaviour that need to become second nature in their implementation.

Principles of Measurement

Many students, not just beginners, do not seem to know how many pitfalls there are in taking a simple reading from an instrument. First of all, has the instrument been adequately calibrated? When the instrument has been calibrated, what is the sensitivity and is there a problem with zero drift or sensitivity drift? Is the characteristic being measured linear or are there any non-linear effects? With regard to readability – the closeness to which a scale can be read – how much readings deviate from known inputs (accuracy) and the relation of this to the problem of precision should be ascertained. These are just a few of the features about taking readings that any experimentalist has to bear in mind.

Errors and the Statistical Analysis of Data

Closely related to the problem of measurement is the problem of errors. The difference between systematic and random errors has to be appreciated, closely followed by the basics of uncertainty analysis, as well as what happens to the errors when quantities have to be added, subtracted, multiplied, divided and raised to powers. These concepts are not intuitively obvious to students and have to be drilled into them. Again, until they become second nature.

The statistical analysis of data is the logical follow-on from a consideration of errors. Measures of dispersion and their significance for different types of error distribution need to be appreciated. When is an item of data significant and when is it spurious – in other words, when can it be ignored and when does it have to be taken into account? Again, this is not always obvious to the student new to experimental work.

Log Books – the Preservation of Data

When students first start on a laboratory course, they are invariably told to purchase laboratory report books, but they are not always told to use log books. The result is an unfortunate tendency to use odd scraps of paper – which get lost. If they use log books, not only can their work be checked by the lecturer in charge of their laboratory course, but they can more easily develop tidy methods of recording information (all types of practical information, not just experimental results) and, above all, they can refer back to their work at a later date.

Report Writing

It goes without saying that reports should be written up as soon as possible after the experiment. In fact, some universities insist that short reports should be written up and handed in at the end of the practical session before students leave the laboratory. This is not always realistic, particularly in courses beyond the second year where the work is likely to be much more complex and the treatment of results more detailed. However, whichever method is used, a strict discipline needs to be imposed upon the manner of the writing, otherwise many students float off into unfocused soliloquies that are totally inappropriate to the business of technical reporting.

The British method is to require reports to be written in the past tense and the passive voice, ie *such and such a thing WAS done* or *such and such a procedure was carried out*, and not *I did this* and definitely NOT *I am doing this …*

There are three tendencies which have to be ironed out, specifically:

- The use of the active voice: we are not interested to hear that THEY had carried out the experiment; we can assume that;
- The use of the present tense: they are reporting on something that they have already carried out; it is in the past and so a past tense needs to be used;
- A regrettable tendency, particularly with weaker students, is to simply present a set of instructions – as if they were telling the lecturer how to perform the experiment.

There is a tendency for students to think that writing reports, or writing anything, is easy. This comes out of inexperience. It is not easy. It is possible to develop a great facility in the art by sheer practice, but it is never easy.

Design of Experiments

The ability to design effective experiments is a neglected skill. Even in laboratories that present well-structured training, this skill tends to be neglected. This is possibly because the design of experiments will not concern students until the later, usually postgraduate stages of their education. However, it is vital to learn the salient features of this art because in industry or in advanced postgraduate work, the difference between a carefully designed experiment and one that is just cobbled together can be the difference between being able to obtain meaningful results and obtaining no results at all.

Some of the typical design features that should be considered are as follows:

- A design that, when one comes to analyse the results, leaves one with four unknowns and only three simultaneous equations;
- If, in the analysis of an experiment, it is necessary to calculate the difference between two quantities of similar magnitude, then the resultant error bound is likely to be increased enormously;
- If there is too much symmetry in the design, the system might be intrinsically unobservable. No matter how many instruments are added, the actual architecture of the experiment might mean that it is mathematically impossible to observe the results; the only solution to this is a redesign;
- Similar to the observability problem, there is a controllability problem. No matter what inputs one

tries to use, some parameters can be uncontrollable. Again, the only solution to this is a radical redesign;

- Sensitivity drift, which occurs when changes in other parameters cause the sensitivity of the parameter being measured to change;
- Cross-talk;
- Sensitivity to noise;
- A variety of problems can occur due to non-linearities in the system. These can range from simple non-linear mapping between the instrumentation and the parameter being investigated (Ph measurement is a well-known example of this problem) to jump-resonance, hysteresis, parasitic oscillations, threshold and dead-band problems.

There are many more potential design problems, but an awareness of them all can and should be taught. An appreciation of how to avoid them is not very difficult.

This is considered to be a vital skill that is often overlooked when honing students' experimental training. Since the very act of attempting to design their own experiments causes students to reflect on the intricacies of experimental procedures, it really is a vital step that complements all of the other laboratory training.

HOW TO IMPART EXPERIMENTAL SKILLS

The crux of training a student who is completely new to laboratory work is to assume no background whatsoever, no matter what his/her age. At the same time, students must not be made to feel inadequate because their background knowledge is meagre. A structured approach is required that rapidly imparts the more factual background [5]. This is often best accomplished by means of tutorials in which the more basic background can appear to be drawn out of students – although in reality, they are having to be given the information. Simple case studies can then be introduced in which problems can be deliberately introduced and thoroughly discussed.

At this stage, very simple practical tasks that take only 10-15 minutes apiece can be introduced. These are not specifically to impart factual knowledge, but rather to enable the student to develop a *feel* for the equipment and to encourage an innate attitude to best practice. It is important to remember that we learn through ALL of our senses [1][4][6]. The actual physical experience of handling objects in the laboratory gets laid down as a memory that can act as a latch, which, in turn, can open the door to more involved background memories about laboratory procedure. The texture of a material being handled can be the trigger later on for a whole group of associated memories. In some subject areas the actual smell of the material or the equipment, or of a particular laboratory environment, can trigger a whole host of associated relevant remembered practical experiences.

The important point here is that the network of remembered experiences must be pleasurable. If this can be accomplished, then the student will look forward to the laboratory work and develop a flair for it. It has been suggested that when someone is said to have a flair for a particular subject, all that has happened is that their initial experiences in that area have been so pleasurably memorable and they become so keen on it that they subconsciously make the effort to learn the subject matter in a thorough fashion. The key is to make the subject so pleasurable that they subconsciously make the effort to thoroughly learn the basic routines in that area.

These simple routine laboratory exercises need to be followed by practical demonstrations of more formal complex experiments, and should be followed by group treatment and discussion of the results. Experience suggests that it is only at this stage that students can be let loose on formal full-scale experiments. Two things should be mentioned here:

- The German practice of giving students the laboratory sheets a week beforehand and then questioning them to make sure they have fully prepared before allowing them to perform the experiments should be followed. Again, experience shows that this approach leads to a fuller appreciation of the work being carried out;
- There should be no more than two students working at a given experiment station. Every experiment should be followed by a formal report. These reports should, of course, be marked and returned to students promptly in order to reinforce the learning experience. There is no point in the reports all being collected and marked at the end of a semester – there is no educational experience to be gained from that.

The first group of full-scale experiments should be closed, self-contained exercises, but they should be followed as quickly as possible by open-ended experiments. It has been amply shown that it is only with open-ended experiments that students can be stretched and given a chance to exercise their ingenuity. It is only with open-ended experiments that they can demonstrate that they have a thorough grasp of the purpose of various experimental procedures.

The next step in complexity is the actual designing of experiments. Again, this requires a structured approach. This stage will not have been reached until the later years of a course and so it would be expected that the necessary theory would already have been covered in formal lectures. One approach that has been tried is to use a portfolio of case studies and thoroughly discuss all the features they raise in seminars. However, this should ideally be followed by a suite of comprehensive design problems that could be tackled using a student-centred group approach.

DISCUSSION AND CONCLUSION

A comprehensive list of skills that need to be imparted if a student, completely new to practical work, is to become a competent experimentalist are presented in this article [7][8]. The list does not claim to be exhaustive. However, even if they never subsequently earn their living in a hands-on manner, they need to be aware of the problems faced by experimentalists and to have a sympathy for them.

The suggested approach is a compendium of methods tried by various educators and found to work. It requires a strict regime and it is envisaged that it would span a three-year undergraduate course – or possibly four if the design stage is split between the bachelor and the Master levels.

In earlier work, the author has reported on the experience of taking students from the French two-year DUT system and placing them in the final year of a British degree course [9]. Those students found themselves going from a very strict regime, where they were expected to learn routines but not to question the reason for those routines, to a very laid-back system where they were expected to supply their own drive and where the practical work, in the form of projects, was often very open-ended. They initially suffered a profound culture shock, but then responded better than the British students. This has led to the suggestion that the best approach with students is to start with a more formal rigid instructional approach for the first two years and then move to a more student-centred regime in the later stages.

Some centres have experimented with group design work to foster the student-centred approach. However, experience tends to show that with all laboratory procedures there is an understandable *clustering at the back of the laboratory* tendency among weaker students and this cannot be allowed to happen.

This article is concerned with student performance in the laboratory and in performing practical work in general. For that reason, project work has not been discussed, nor has student-centred work in general. There is obviously a connection and students who have been through the practical training regime outlined in this article should find it considerably helpful in performing the practical side of their project work. However, there are many other skills that are needed for successful project performance [8][10]. A discussion of them would constitute a completely separate paper.

If students are not introduced in an orderly and planned manner to practical work, then their performance in the laboratory can be a danger to others and they can do serious damage to expensive equipment. For these reasons, they have to be taught how to behave when handling equipment and to have consideration for others around them. These are rather obvious sentiments, but ones that are surprisingly often ignored. If they have not been trained to develop a methodical approach to their work and how to treat results, then their laboratory scores will be low and they will become discouraged. Furthermore, if they have not developed a methodical approach to practical work, they will become further discouraged. They will not enjoy the work, will lose interest and, then finding the subject uncongenial or difficult, will drift out of engineering.

The methods for training a student in laboratory work described in this article have been tried with students over the past 20 years. The ones mentioned here are those that have held students' attention and consequently have been found to be most effective. Above all, the requirements in the later stages to design their own experiments develops a reflective attitude that helps to round off the whole experience and deepens the skills gained into intuitive instincts. The author suggests that this regime will turn the initially diffident student into a competent and safe experimentalist.

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BIOGRAPHY

George Page was born and went to school in Lancashire in England, UK. He attended the universities of Wales (at Bangor), Manchester and Liverpool. His initial subjects were physics and mathematics but his current teaching and research interests are in intelligent and adaptive control systems and, in particular, signal shaping using fuzzy logic techniques.

He has considerable experience in engineering education and has served on numerous national and international committees. He has been an examiner in control engineering for the British Engineering Council, guest editor for several international journals, and is the author of one book, and many papers and articles. He has taught for the Open University and Liverpool *John Moores* University in the UK, and also has close links with several universities across Europe. He is currently a professor of control engineering at Hochschule Wismar in Wismar, Germany. He was awarded the UICEE Silver Badge of Honour in September 2006.