Introducing measurement uncertainty to undergraduate science and engineering students

Preamble: This document is adapted from a paper that first appeared in the proceedings of the 2004 conference of the Metrology Society of Australia[1]. While the document has an 'Australian perspective', we believe the issues raised regarding teaching uncertainty have relevance to educators elsewhere introducing measurement uncertainty to undergraduate classes.

Abstract

The ISO Guide to the Expression of Uncertainty in Measurement (GUM) has yet to impact seriously on the way uncertainty is taught in tertiary education institutions. Current methods used for determining uncertainty presented to undergraduates tend to be inconsistent and sometimes conflicting. Here we discuss some current practices relating to introducing measurement, error and uncertainty in introductory physics subjects. Modifications to existing curricula are suggested which are intended to introduce contemporary methods of determining measurement uncertainty to students. We expect that adopting a consistent, internationally recognised, approach to calculating uncertainty based on the GUM will reduce some of the frustration experienced by students caused by conflicting advice regarding uncertainty evaluation. In addition, the ability to apply the GUM will be a sought-after competency valued increasingly by industry and analytical/research laboratories. Likely challenges to the large scale introduction of the GUM to undergraduate classes are considered.

Introduction

First year physics subjects offered at universities typically consist of three hours of lectures and a three hour laboratory session each week for twelve or so weeks. While recent trends have been to reduce the amount of physics in, say, engineering and bio-science courses, many of these courses still rely on the laboratory component of an introductory physics subject to expose students to the basics of careful measurement, experimental design and the treatment of scientific data. In a study designed to reform the laboratory physics programme for engineering students, it was clear that engineers in at least one large metropolitan university in Australia expected the introductory physics subject to teach the basics of measurement and uncertainty to incoming engineering students [1]. The sense was that measurement and error, though important, were not topics that engineers themselves would teach. As one senior engineering academic put it:

When I talk to physicists, they are very much more interested in errors and uncertainties than any engineer I've ever met.

Senior engineering academic, metropolitan university in NSW, Australia

Clarifying the purpose and expected learning outcomes of laboratory work for students is important, as sustained pressure exists to re-evaluate 'hands-on' laboratory based work and to consider other options, such as dry laboratories in which computer based simulations supplement or replace conventional experiments [2]. In addition, it is important to recognise that from the student viewpoint, laboratory work can be a high anxiety and frustrating activity, partly due to the fact that the anonymity enjoyed in large lectures is replaced by the high visibility accorded to experimental work.

Since to 1980s there have been several attempts to progress beyond conventional recipe based experiments, where there is little evidence of serious student engagement, to approaches which attempt to offer students experiences closer to those of scientists working in a laboratory [3]. These experiences include using theory to decide which data should be collected, engaging in scientific enquiry by making predictions, and critically analysing experimental data [4]. Taking the opportunity to link laboratory work to material presented in lectures in order to reinforce and extend basic principles has also been shown to be important [1]. Equally important is to choose contexts for experiments with which students can readily and positively identify.

Student background in measurement

The range of students' backgrounds and preparedness for study of introductory physics has altered significantly in recent years to an extent that many academics teaching first year physics subjects assume little formal knowledge of physics on entry. With specific reference to prior knowledge of experimental procedures such as measurement, there have been few studies that have considered this matter in detail.

[1] Kirkup L (2004) *Reforming the teaching of uncertainty to undergraduate science and engineering students* proceedings of the MSA (Metrology Society of Australia) 2004 5th Biennial Conference, Melbourne, March 2004 pages 21 to 25.

One study that has been carried out on student understandings about measurement suggests that students believe that it is possible to determine the true value of a measurand and that the scatter obtained when measurements are repeated are attributable to mistakes [5]. The goal of measurement is seen by these students almost exclusively as acquiring a single 'point' value for the quantity under investigation. Students regard any disparity between their result, and what they anticipate to be the true value to be, as 'their fault' [6]. Work carried out on university students prior to beginning a first year physics laboratory program suggests that students' reasoning regarding measurement can be broadly placed in one of two categories [7]. In the first category, referred to as 'point reasoning' students regard a single measurement as sufficient to establish the true value of a quantity. Even if more measurements are made, they are not combined, but rather the most frequently occurring value is adopted as the true value. In the second category, referred to as 'set reasoning', students regard each measurement as only an approximation to the true value. All values collected are required for a best estimate of the true value, as well as establishing a measure of the spread of the values. Prior to instruction, the number of students in the 'point reasoning' category outnumber those in the 'set reasoning' category [8].

Existing approaches to teaching uncertainty

Often, activities that take place in the laboratory such as consideration of errors and uncertainty, are divorced from material presented in lectures. Students often do not see a link between lecture material and the laboratory program and indeed many laboratory programs are developed in such a manner that academics themselves are unclear as to the extent to which the laboratory and lecture elements of a subject should be integrated [9].

As an introductory physics laboratory program may have many goals [10] such as fostering effective group work, encouraging participation in experimental design and the acquisition of particular manual skills, it is usual for measurement and uncertainty to be focussed upon in a handful of laboratory sessions at most. The intention and expectation is that the experience and insight gained into measurement and uncertainty is then persistently applied in succeeding laboratory sessions.

In large first year classes, the responsibility of introducing measurement and uncertainty to students is often that of part-time or casual staff, such as PhD students acting in the capacity of laboratory instructors or demonstrators. These demonstrators often communicate their own preferred methods for uncertainty calculation. The result is that advice given to students on basic matters such as calculating an uncertainty based on repeat measurements of a single quantity often conflicts with other demonstrators and can even be contradictory. This should come as no surprise, as inconsistency of usage of such terms as error, uncertainty, precision and accuracy within laboratory manuals and undergraduate textbooks is widespread [11]. An example of the use of the word 'accurate' taken from first year physics laboratory manuals gives some flavour of the difficulties students can encounter.

An <u>accurate</u> instrument is one that always gives the same reading when used to measure the same stimulus.

1st year physics manual, UK University

An instrument which we believe produces small or negligible systematic error is said to be <u>accurate</u>.

1st year physics manual, Australian University

Suggested reforms to the teaching of uncertainties

Reforms to the teaching of measurement and uncertainty should begin with a review of the primary purpose of the subject under consideration. For example, is a physics service subject for engineers designed to prepare students for later specialist topics they will cover in their engineering studies? If it is a service subject for bioscience students, is its purpose to introduce physics concepts underlying phenomena likely to be encountered by bioscience students? Such a review is likely to suggest contexts in which to introduce error and uncertainty that are likely to appeal to students. Context and relevance are regarded (by students at least) as key motivating factors, and as such affect the attitude of students towards subjects perceived as lying outside the areas of their major study [12]. Assuming that principles of measurement and uncertainty *are* key elements of the subject, then figure 1 offers a possible scheme for the integration of lecture and laboratories designed to introduce measurement to first year undergraduate students.

It would be not be prudent to assume that any student will view the accumulation of data in an experiment as an absorbing experience in itself. Prior to entering the laboratory there is merit in clarifying *why* measurement and uncertainty are important to the particular discipline in which students are majoring. For example, where students are drawn from the forensic sciences or chemistry, an emphasis could be brought to the role of consistent methods of establishing and expressing uncertainty in analytical laboratories whose services need to be accredited. This introduction should lead, in a natural manner, to consideration of the GUM [13].

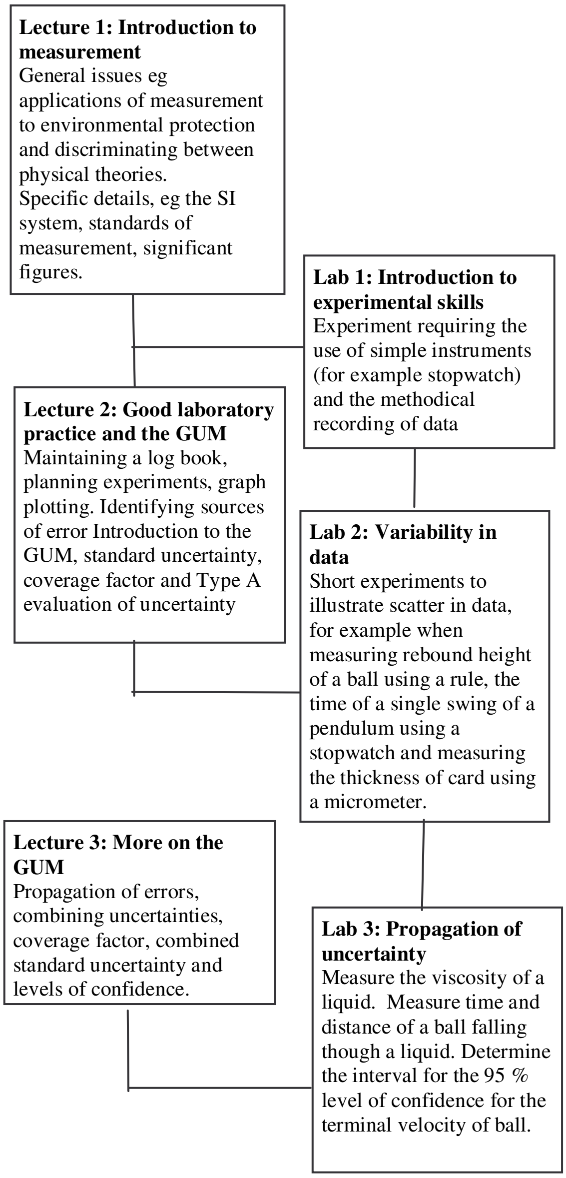

Figure1: Scheme for introducing measurement and uncertainty to undergraduate students

Introduction of the GUM is the most radical proposal contained in Figure 1. Reasons for introducing the GUM to undergraduates include,

- The GUM has international recognition and authority.
- If the GUM is consistently applied, students will be spared much of the frustration caused by encountering a variety of methods for determining uncertainty (ie having to learn and unlearn methods of determining and reporting uncertainty).
- Increasingly, industries and regulatory authorities require consistent implementation of the GUM, therefore there is growing demand for workers at all levels to be conversant with the GUM.
- Motivating students to build on, exploit and apply the statistical principles they encounter.

It would be counterproductive to attempt too thorough a treatment of the GUM at first year level. Recognising and dealing with variability in values through Type A evaluations of uncertainty, the introduction and consistent use of vocabulary used in the GUM, such as standard uncertainty and coverage factor and the capacity to deal with the propagation of uncertainties where individual components in the uncertainty budget are considered to be independent, are worthy ambitions for a practical introduction to measurement and uncertainty.

Discussion

There are several significant challenges to be faced if clarity and consistency are to be brought to the way measurement and uncertainty is taught to undergraduates.

Before wide scale adoption of the methods contained in GUM takes place in universities, there needs to be a ‘critical mass’ of academics who are both familiar and comfortable with the methods and vocabulary contained in the GUM. There has been no formal study regarding the prevalence of use of the GUM in academia, but anecdotal evidence suggests that there is little awareness of the GUM and that much needs to be done to ‘spread the word’.

Appropriate teaching materials need to be available aimed to support academics, laboratory demonstrators and undergraduate students, that speaks ‘their language’. Material is already available to assist a mature audience who must routinely apply the GUM [13], [14]. However, most documents dealing with the GUM are densely written, with few in the way of worked examples that academics and undergraduates can relate to [15],[16],[17]. Textbooks that introduce experimental methods to undergraduates largely avoid the GUM, and this is a situation that must be remedied before awareness of the recommendations contained in the ISO document become commonplace [18]. A good sign is that articles in education-type journal that discuss the use of the GUM are beginning to appear [19]

Even when online and textbook resources become available that deal with the GUM, the primary source of written information for students will remain the laboratory manual. Often due to matters that are given higher priority, laboratory manuals are generally not updated sufficiently often to give them currency. It is likely that, only when laboratory manuals are revised to include the GUM will elements of the GUM become embedded in the undergraduate curriculum.

Teaching materials can only go so far at getting the ‘message across’. Before students become comfortable with contemporary methods of determining and reporting uncertainty, those that have direct contact with those students in the laboratory, namely the laboratory demonstrators, must themselves reach a level of comfort. This may prove to be the most demanding challenge, as demonstrators may have many years experience of doing uncertainties 'their way' and unless they see the benefits of employing another approach, distrust of any new method will be relayed to students.

Conclusion

With the development of the GUM and its increasing impact on the way uncertainties are calculated and expressed in industrial, academic and regulatory environments, it is opportune that the purpose and methods of measurement and uncertainty as taught to undergraduate students be reviewed. The review should consider the needs and expectations of the students with particular reference to applying methods of measurement and uncertainty in contexts that students are able to relate to.

Adopting an approach to uncertainties consistent with the GUM should bring clarity and consistency to the use of terms such as accuracy and uncertainty. This, in turn, is anticipated to have a beneficial effect on the attitude of students towards the study of (and confidence to deal with) uncertainty in measurement. How the GUM might be introduced into the undergraduate curriculum deserves to be the subject of debate. Avoiding or ignoring the GUM completely may become untenable for academics as industry, regulatory authorities, and quality assurance bodies move towards its consistent implementation.

Introduction of the GUM to undergraduate subjects will require the creation of appropriate teaching and learning materials. Initiatives are also required to support those demonstrators and academic staff intent on adapting their teaching of laboratory based work to include the GUM.

References

[1] Kirkup L, Johnson S, Hazel E, Cheary R W, Green D C, Swift P and Holliday W, 'Designing a new physics laboratory programme for first year engineering students', *Physics Education* vol 33, 1998, pp 258-265.

[2] Pearce J M, 'The role of IT in teaching experimental science: from a multimedia perspective', *Dry Labs Workshop Proceedings, UniServe Science, Sydney* 1996, pp 4-8 URL: science.uniserve.edu.au/pubs/procs/drylabs.pdf

[3] Boud, D, Dunn J and Hegarty-Hazel E, 'Teaching in Laboratories' 1986 (SHRE and NFER-Nelson, Surrey) chapter 7.

[4] Cheary R, Gosper M, Hazel E and Kirkup L, 'Revitalising first year physics laboratories at the University of Technology, Sydney', *Australian and New Zealand Physicist* vol 32, No. 6, 1995, pp. 119-124.

[5] Sere M-G, Journeaux, R and Larcher C, 'Learning the statistical analysis of experimental error', *International Journal of Science Education* vol 15, No. 4, 1993, pp. 427-438.

[6] Fairbrother R and Hackling M, 'Is this the right answer?', *International Journal of Science Education* vol 18, No. 8, 1997, pp. 887-894.

[7] Lubben F, Campbell B, Buffler A and Allie S, 'Point and set reasoning in practical science measurement by entering university freshmen', *Science Education*, vol 85, No. 4, 2001, pp 311-327.

[8] Buffler A, Allie S, Lubben F and Campbell B, 'The development of first year student ideas about measurement in terms of point and set paradigms' *International Journal of Science Education*, vol 23, No. 11, 2001, pp. 1137-1156.

[9] Cheary R, Hazel E, Gosper M, and Kirkup L, 'Reforming the undergraduate science laboratory, *Research and Development in Higher Education* vol 16, 1995, pp. 129-137.

[10] White, R T, 'The link between laboratory and learning', *International Journal of Science Education* vol 18, No. 7, 1996, pp. 761-774.

[11] Kirkup L, 'Should we be more systematic about uncertainty?' *Proceedings of the 15th AIP Biennial Congress, Sydney* 8-11 July, 2002, pp 253-255.

[12] Wood L, Mather G, Logan P and Kirkup L , 'Teaching Mathematics and Physics for Engineers: Reflections from the Back Row' *Proceedings of the 5th International Congress on Industrial and Applied Mathematics*, Sydney, Australia 7-11th July, 2003, pp 295-300.

[13] RE Bentley, 'Uncertainty in measurement: the ISO Guide Monogr 1: NML Technology Transfer Series, ISBN 0-9750744-0-7, CSIRO, Sydney, 2003.

[14] RB Frenkel, 'Statistical background to the ISO GUM', Monogr 2: NML Technology Transfer Series, ISBN 0-9750744-1-5, CSIRO, Sydney, 2003.

[15] ISO 'Guide to the Expression of Uncertainty in Measurement' (Geneva, Switzerland: International Organisation for Standardisation), 1995.

[16] EURACHEM 'Quantifying Uncertainty in Analytical Measurement' (London: Laboratory of the Government Chemist), 2000.

[17] NIST Technical Note 1297 'Guidelines for Evaluating and Expressing Uncertainty of NIST Measurement Results' (*Washington: U.S. Government Printing Office*), 1994.

[18] Kirkup L, 'A guide to GUM' *European. Journal of Physics*, vol 23, 2002, pp. 483-487.

[19] Allie S, Buffler A, Cambell B, Lubben F, Evangelinos D, Psillos D and Valassiades O , 'Teaching Measurement in the Introductory Physics Laboratory' *The Physics Teacher*, vol 41, 2003, pp. 394-401.