

## **Metrology as part and parcel of training programmes for science and engineering**

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***Abstract.** At many universities and training institutes education in metrology or measurement science is in strong competition with upcoming disciplines. Its importance for science and engineering remains, however, evident. Advanced instruments make measuring almost a routine activity, but it is shown that a critical approach when performing and evaluating measurements is still of vital importance.*

*Keywords: education, measurement science, metrology*

### **1. Introduction**

The role of metrology is crucial in almost every aspect of modern society, although not always recognized as such. Fields where measurement plays an evident role are, for instance, medical and health care, transport and trade, production and factory management, communication and navigation. An incorrect measurement can have a tremendous economical and societal impact. The most striking illustration of the former is the crash of the Mars Climate Orbiter in 1999. The spacecraft should remain at an altitude of about 150 km above the planet's surface, however approached it at some 57 km. This catastrophic navigation error appeared to be caused by mixing up units: some data were expressed in Imperial Units, whereas these data were interpreted as SI units.

Many more examples can be found of erroneous measurements having caused unintended damage or even worse: the death of people. Correct measurements (which implies correct interpretation of the results as well!) are definitely of paramount significance. Obviously, human activity is never free from errors. Reducing the error probability however should have high priority, and starts with adequate education and training, also where measurements are concerned.

This paper discusses the question which elementary metrological topics should at least be part of the curriculum of (technical) universities and institutes for vocational training. In this paper, no distinction between the expressions “metrology”, “measurement science” and “measurement and instrumentation” will be made unless explicitly indicated.

### **2. The essentials**

Most measurements are executed by non-experts in metrology. Fortunately, modern measurement systems have user-friendly interfaces, and go with application specific software for the processing of the measurement signals, simplifying the execution of a measurement. However, this does not relieve the user from a critical attitude with respect to the instruments used, the execution of the measurement, and above all the interpretation of the final results. Depending on the application, more or less basic knowledge is required to perform measurements in an adequate manner. Therefore, the curricula of engineering schools, technical universities and other special training institutes should contain at least some basic courses on measurement (and instrumentation). However, forced by circumstances, many

training institutes have reduced or will reduce the time students have to spend on metrology. One of the causes setting pressure on the educational programme is the newly introduced Bachelor-Master structure at universities, especially those with a traditional undivided program. The bachelor study should last 3 years and offer a complete, self-contained programme in which all essential subjects of the discipline have got their place. Cost reduction is another reason to minimize practical training sessions and exercises, which are essential for learning the practice of measurement and the proper evaluation of measurement results. This topic is discussed in section 3. Further, metrology is often considered as old-fashioned, dull, not trendy, and of little interest by both teachers and students. This applies in particular to the legal aspects of metrology, to standards, traceability, calibration and to uncertainty evaluation. For most teachers the core of measurement science seems far away from daily practice, and they don't pay much attention to these matters. Finally, there is a noticeable change in learning philosophy, starting already at primary schools: decide yourself what to learn; find it yourself on the Internet (considered to present the "truth") and a lack of critical perception.

However, metrology is experiencing an evolution. The traditional industry needs measurement instruments for a growing variety of quantities over an ever extending range, with smaller uncertainty, higher environmental demands and at lower costs. Upcoming technological areas (nanotechnology, biotechnology) require the development of new measurement equipment. In many areas measurement science becomes more and more relevant (clinical chemistry, safety, security, food). Many areas are deficient in metrological expertise, on a general, professional and expert level. That is why any engineer, designer and scientist should at least have some knowledge about the topics in the following list:

- units and dimensions
- standards and traceability
- uncertainty evaluation
- the effects of quantization and sampling
- specifications of (measuring) instruments
- general error reduction concepts (feedback, balancing etc.)
- the effects of instrument loading
- the major operation principles of sensors commonly used in manufacturing and testing
- the major principles of AD- and DA-conversion
- the major principles of signal conditioning (amplification, filtering, modulation)
- elements of signal processing.

Many textbooks on Measurement Science include all or most of these elements indeed. These works differ mainly in the detailing and the choice of special additional topics. Obviously, no undergraduate course should go without these basic elements. Signal processing is often treated in separate courses, and the same holds for signal conditioning and conversion. Aspects of legal metrology are found almost exclusively in special training courses for employees of quality and certification laboratories. Only a few works present a comprehensive overview of measurement science including the aspects of legal metrology, the history of standards and units, aspects of traceability and certification and many others, as for instance in [1-2]. The first is an 1800 pages book printed in 3 volumes, the second is a

collection of texts, illustrations, animations and exercises, available on the Internet [3]. General textbooks do not give a great deal of legal metrology. That is why many graduates have no idea at all about standards, uncertainty and related matters.

The effects of this lack of knowledge become apparent already in advanced bachelor courses, during the master study and even in technical reports and papers. Every teacher recognizes these typical examples:

- reporting experimental data in as many decimals as presented by the calculator (average of 2.17835406 V; accuracy 2.7825 %)
- wrong, non-SI units and their notations (in., °F, mmHg, hp,...)
- wrong notations (KHz, Khz, khz, sec,...)
- graphs with wrong or no scale indication, in which the measurement points are connected by straight lines and without any tolerance discussion (but nevertheless accompanied by the phrase "the experimental data are in good agreement with theory").

Admittedly, in most cases the actual meaning can be deduced from the context, but nevertheless it is wrong, and sometimes these carelessness may have serious implications. Teachers have the duty to constantly alert students to such errors, and stress the importance of accuracy with respect to reporting of experimental data. "What's learnt in the cradle lasts till the tomb".

### 3. Practical training

Students (and even more experienced) are often not aware of measurement errors caused by, for instance, loading, insufficient quantization levels, too a low sampling rate, etc. Such errors may be discussed extensively in theoretical courses, but during an experiment they are not immediately and clearly visible. So, they should be made aware during practical training. This is why practical exercises in measurements are of paramount importance. Metrology can not be learned from books alone.

Examples:

- improper signals without noticing (slew rate, bandwidth, overload, unexpected interference): "always use an oscilloscope"
- some signal generators with 50  $\Omega$  output impedance expect a 50  $\Omega$  load (corresponding with the value on the display); when loaded with a much higher impedance, the display value may be half the actual one when not corrected for
- ignoring particular deficiencies of sensors (the low cut-off frequency or the resonance frequency of a piezoelectric accelerometer, the wavelength dependency of the sensitivity of optoelectric and acoustic devices, non-linearity of a PSD, and many others)
- wrong interfacing of sensors (ignoring cable capacitance at voltage readout of a piezoelectric accelerometer, unintentional filtering, introducing non-linearity by loading a potentiometric sensor)

All these errors are made due to lack of knowledge on the physical principles underlying these sensors, on incomplete models of the measurement configuration and implicitly trusting system specifications and simulations. Students should be made aware of measurement errors

and should quantify them in an appropriate way. In [4] a laboratory environment that enables students to familiarise with the total spectrum of skills that are to be learned for performing correct and effective measurements has been introduced. The environment comprises both measurement equipment and virtual tools for the execution of real measurements and the proper interpretation of the results.

#### 4. Virtual versus real

Cost reduction is often a motive to move from real measurement equipment to virtual instrumentation. The computer is gradually taking over more and more instrumental functions. The development of “virtual instrumentation” is still expanding, driving back the usage of conventional real instruments. Obviously, virtual instruments have a lot of advantages, but will never take over the measurement itself. The advance of virtual instruments simplifies the set-up of a measurement, however it also tends to mask possible measurement errors, since a measurement takes place in the real world, and the training process needs, at least partly, be performed in the same real world.

Learning by doing appears to be an essential supplementation to lectures and text books, in particular where metrology is concerned. Embedding measurement science education within a design project is an effective way to motivate students. The success of such an approach depends on the internal coherence and a careful balance between the various disciplines. An example of such a problem based learning project is the “Water Tower” [5] of the Vrije Universiteit Brussel, in which students are faced with a combination of various disciplines from preceding courses in a single measurement and control system (Figure 1). Evaluation of this approach shows that embedding theory in practical cases stimulates the student’s creativity and motivation.



Fig. 1. Water Tower setup from the Vrije Universiteit Brussel [5]

Another example where metrology is successfully integrated in a practical training course is the first-year Design Project at the Dept. of Electrical Engineering, University of Twente, where three first-year courses are merged: analogue electronics, digital electronics and measurement instruments. Figure 2 gives an impression of this project. After the lectures

students are tested not only on the theoretical knowledge they should have gained, but also on the ability to apply and integrate this knowledge in a practical situation. Groups of four students select a topic from a list with assignments to design a specific measurement system. Within one week and with limited resources they have to design, build and test that system, using standard analogue and digital components only. The pictures show the successful design of an electronic calliper and an electronic lung volume meter. This project is one out of a series of projects students have to pass during the first year of the Bachelor phase.

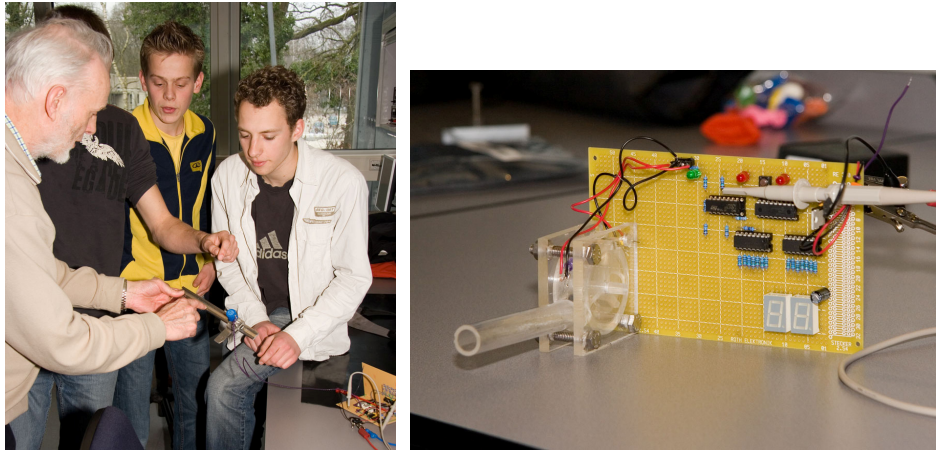


Fig. 2. A first-year design project where courses in electronics and metrology are merged.

## 5. Conclusions

Measurements stand at the basis of our knowledge and are essential in many areas of human activity. Engineers and technicians, and anyone confronted with critical measurements, should have some basic knowledge of metrology. Therefore, metrology is an indispensable component within the curricula for higher education. Virtual instruments can not replace all laboratory facilities, but can, when properly embedded in challenging student projects, reduce costs and increase the efficiency of practical training sessions.

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